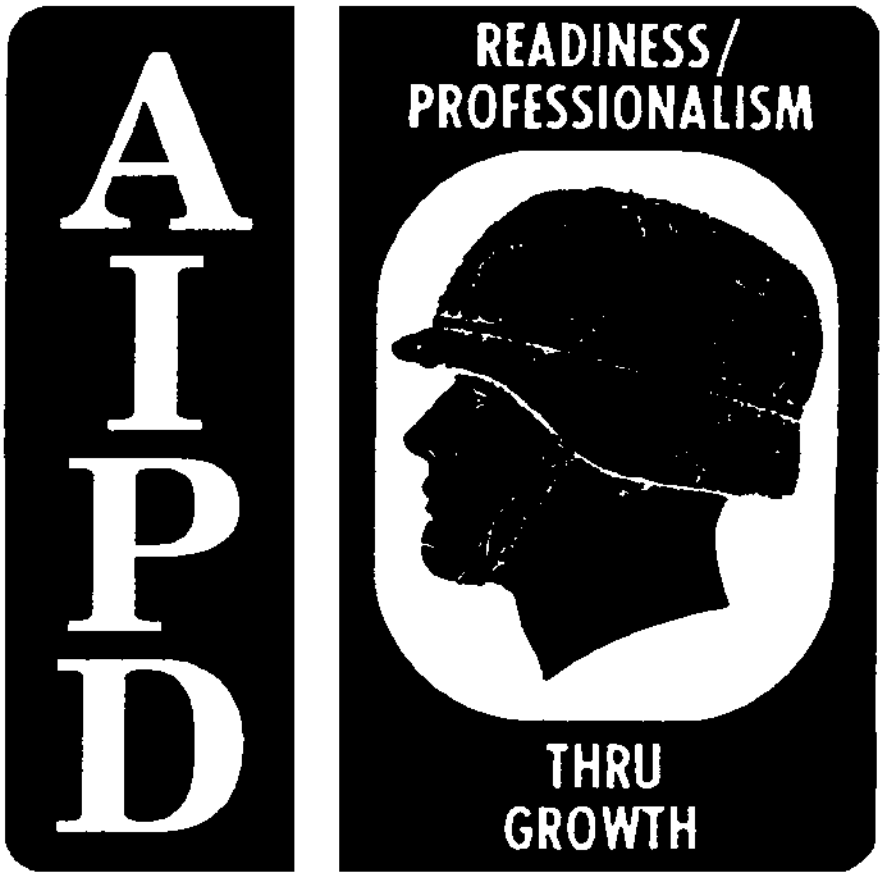
SUBCOURSE
MM0311

EDITION
9

ELECTRON TUBES



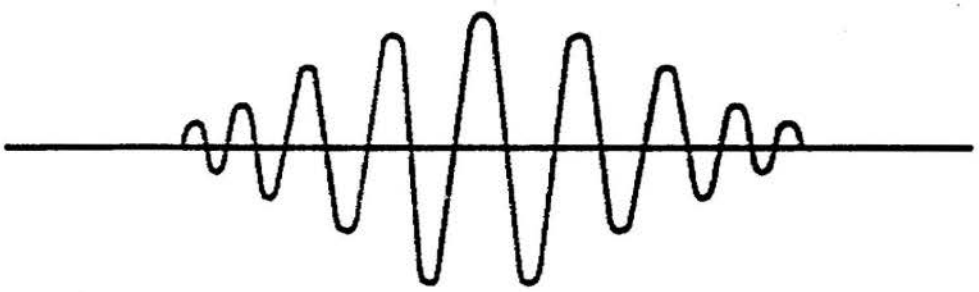
THE ARMY INSTITUTE FOR PROFESSIONAL DEVELOPMENT

ARMY CORRESPONDENCE COURSE PROGRAM

Notice to Students

Use the Ordnance Training Division website,
http://www.cascom.army.mil/ordnance/,
to submit your questions, comments, and suggestions
regarding Ordnance and Missile & Munitions
subcourse content.

If you have access to a computer with Internet capability and can receive e-mail, we recommend that you use this means to communicate with our subject matter experts. Even if you're not able to receive e-mail, we encourage you to submit content inquiries electronically. Simply include a commercial or DSN phone number and/or address on the form provided. Also, be sure to check the Frequently Asked Questions file at the site before posting your inquiry.



NOTE

Proponency for this subcourse has changed from Signal(SS) to Missile and Munitions(MM).

SIGNAL SUBCOURSE SS0311

CREDIT HOURS: 10

CONTENTS PAGE

Information to Student..... ii

Introduction to Lessons..... ii

Learning Strategy..... iii

Resource Requirements..... iv

Lesson 1: Electron Emission..... 1

Lesson 2: Diodes..... 23

Lesson 3: Triode Fundamental..... 57

Lesson 4: Triode Characteristics and Constants..... 88

Lesson 5: Multielement Tubes..... 130

Lesson Solutions..... 165

Subcourse Examination..... 174

Changes to TM 11-662 (C1, C2 and DN1)..... 185

Student Inquiry Sheet 190

VALIDATION INFORMATION

This subcourse has been validated in the field by continuous use for over three years.

Whenever pronouns or other references denoting gender appear in this manual, they are written to refer to either male or female unless otherwise indicated.

SIGNAL SUBCOURSE SS0311, ELECTRON TUBES

INFORMATION TO STUDENT

This is an "unsupervised" subcourse and is designed to give you an understanding of electron tube theory. Although this is an unsupervised subcourse, you should always feel free to seek assistance from your supervisor, peers or someone knowledgeable on the subject matter whenever you encounter difficulty.

The subject of electron tubes has been divided into two signal subcourses. This subcourse, SS0311, is concerned with the general operational theory of tubes. Signal Subcourse SS0312, which you should study next, discusses the various uses and configurations of tubes; such as tube oscillators or amplifiers.

You are urged to complete this subcourse without delay; however, there is no specific time limitation on any lesson or the examination.

INTRODUCTION

In this age of advanced computer technology and probes into deep space which were made possible by the miniaturization of solid state circuitry, an invention by Thomas Edison still plays an important role in communications and our everyday lives. This invention, the electron tube, enables us to enjoy television, radio and safe air travel with pin-point navigational accuracy.

An extremely large variety of electron tubes is used to perform many varied functions. In this subcourse you will study the basic types of tubes and how they function.

***** IMPORTANT NOTICE *****

THE PASSING SCORE FOR ALL ACCP MATERIAL IS NOW 70%

PLEASE DISREGARD ALL REFERENCES TO THE 75% REQUIREMENT.

LEARNING STRATEGY

This subcourse is comprised of five lessons and the subcourse examination, as follows:

Lesson 1: Electron Emission

Lesson 2: Diodes

Lesson 3: Triode Fundamentals

Lesson 4: Triode Characteristics and Constants

Lesson 5: Multielectrode Tubes

Examination

Credit Hours: 10

The lesson objectives which you are to achieve will be specified at the start of each lesson. Study assignments in the technical manual are listed at the beginning of each lesson under text assignments. That portion of the TM which is relative to the lesson has been extracted from the TM and printed with the lesson.

When you have completed the lesson text assignment, answer the lesson exercises associated with each lesson to insure that you understand the subject matter. Check your answers with those provided in the lesson solutions portion of this subcourse. Then, research the question(s) you have answered incorrectly before you proceed to the next lesson.

Once you have progressed through all five lessons you should be ready to take the subcourse examination. Then, mail in the examination punch card to receive credit for this subcourse.

When you see this symbol (√) in the margin of the TM, refer to either change 1, change 2 or the DNI corrections.

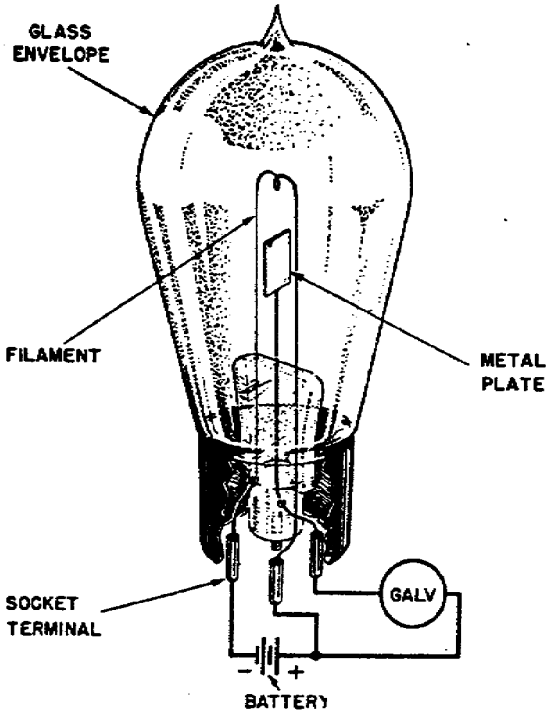
RESOURCE REQUIREMENTS

Texts and materials furnished:

--Subcourse booklet, examination

--TM 11-662, Basic theory and Application of Electron Tubes, dated Feb 1952, w/C1 dated 8 Nov 55 and C2 dated 21 Apr 58. Chapters 1 thru 5 extracted.

--DNI corrections to TM 11-662.



electron emission

lesson one

electron emission

INTRODUCTION

Electronics has been defined as the science dealing with the control of electron flow, especially by the means of electron (or vacuum) tubes. The terms electron tubes and vacuum tubes are used interchangeably to refer to a tube in which a flow of current takes place in an enclosed space. A vacuum tube is one from which the air has been removed to form a partial vacuum.

There are numerous types of electron tubes manufactured; each type differs from the other and has specific electrical characteristics. In this lesson you will study the early experiments in the development of the electron tube and the various types and functions of tubes commonly used today in commercial and military equipment.

TEXT ASSIGNMENT

TM 11-662, chapters 1 and 2, paragraphs 1 thru 12.

RESOURCE REQUIREMENTS

Signal Subcourse SSO 311

LESSON OBJECTIVES

When you complete this lesson you should be able to:

1. Explain the Edison effect.

2. Distinguish tube types.

3. Plot an amplified, rectified, squared, clipped, and generated ac signal.

PAGES 3 THRU 17

ARE EXTRACTS FROM TM 11-662/TO 16-1-255

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

SIGNAL SUBCOURSE SS0311

LESSON 1 - ELECTRON EMISSION

LESSON EXERCISES

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. The action of changing an alternating current into a pulsating direct current is generally referred to as

a. clipping.
b. filtering.
c. squaring.
d. rectifying.

2. An electron tube with four elements is called a

a. diode.
b. triode.
c. tetrode.
d. pentode.

3. Among the many special functions which electron tubes are capable of performing, which of the following tubes does not amplify?

a. diode
b. triode
c. tetrode
d. pentode

4. In 1907, Lee DeForest inserted an extra electrode in the form of a few turns of fine wire between the filament and the plate of Fleming's valve and made a tube called a

a. rectifier.
b. generator.
c. amplifier.
d. clipper.

5. An electron tube capable of sound reproduction from a photographic image on a film is called a

a. generator.
b. audion.
c. phototube.
d. rectifier.

6. Electron tubes are classified as diodes, triodes, tetrodes and pentodes according to

a. their circuit function.

b. amplification factors.

c. the Edison effect.

d. the number of elements.

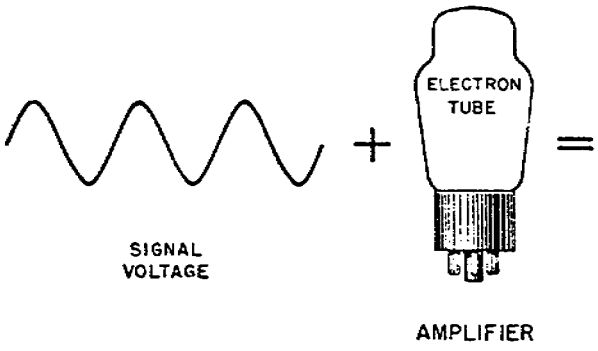
7. In all electron tubes, the emitter of electrons is called the

a. cathode.
c. grid.

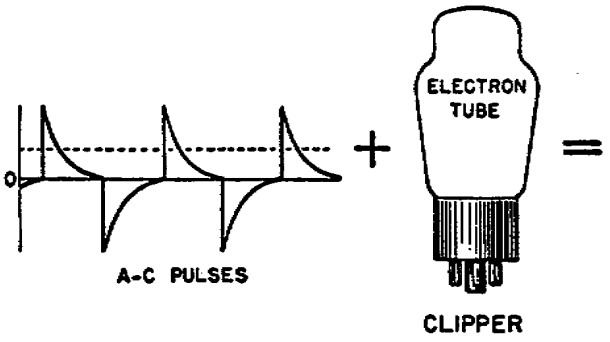
b. anode.
d. plate.

For questions 8-12, draw the correct output for function listed.

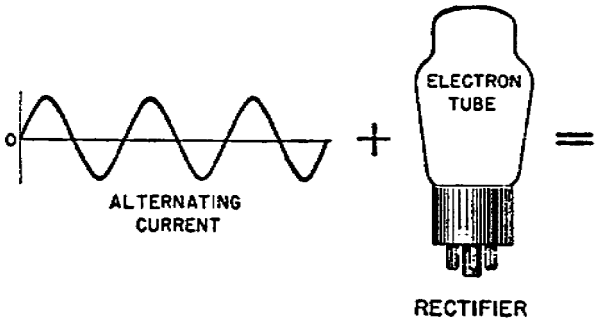
8. Amplifier.



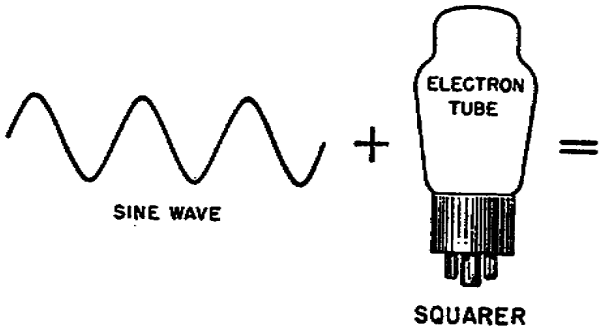
9. Clipper.



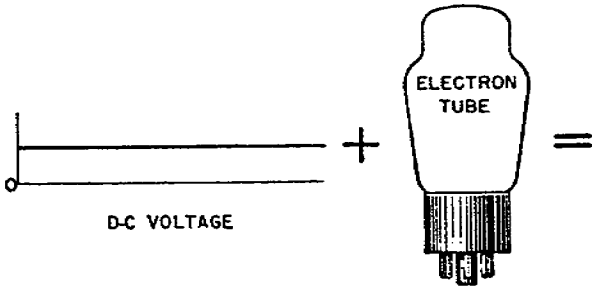
10. Rectifier.



11. Squarer.



12. A-C Generator.



A-C GENERATOR

13. When a filament is heated to incandescence, electrons will flow from it to the plate. This effect was first noted by British scientist Sir J. J. Thomson and is still known today as the

a. Edison effect.
c. hot cathode.

b. rectification.
d. electron theory.

14. If a signal equal to 1 volt was fed into an electron tube and the output signal was equal to 20 volts, the signal was fed into a _____ tube.

a. rectifier
c. squarer

b. amplifier
d. clipper

15. In 1901 the first wireless telegraph signal spanned the Atlantic ocean. The inventor-experimenter credited with this radio signal is

a. Thomas A. Edison.
c. Guglielmo Marconi.

b. Sir J. J. Thomson.
d. J. A. Fleming.

16. Thermionic emission of electrons is the release of electrons from their original material by

a. force of collision with an incoming stream of electrons.

b. cold-cathode ionization action.

c. application of heat.

d. chemical action.

17. The indirectly heated cathode has an advantage over the directly heated cathode in that it can

a. provide almost instantaneous operation.

b. operate from either an ac or a dc source.

c. use oxide-coated emitters, which are more economical.

d. provide a constant temperature despite fluctuations in heating current.

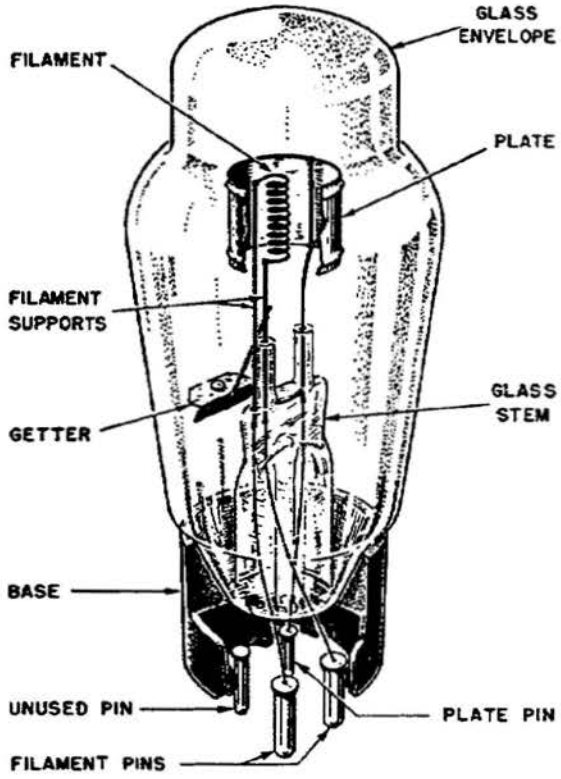
18. What filament material provides the greatest durability and can withstand overloads when used in thermionic tubes?

a. Tungsten.

b. Thoriated tungsten.

c. Oxide-coated nickel.

d. Nickel-coated platinum.


GLASS
ENVELOPE
FILAMENT
PLATE
FILAMENT
SUPPORTS
GLASS
STEM
GETTER
BASE
UNUSED PIN
PLATE PIN
FILAMENT PINS

diodes

lesson two

diodes

INTRODUCTION

The simplest form of vacuum tube contains two electrodes--a cathode and a plate. This type tube is called a diode. Thomas Edison discovered what may be called the earliest diode, his special lamp. The modern diode differs little in principle of operation from the early versions. However, today's diodes are much improved--higher vacuum, longer life and increased ruggedness.

Diodes are used mainly to change alternating current to a pulsating direct current, since it permits current flow in only one direction. In this lesson you will study the construction, operation, characteristics and uses of the diode.

TEXT ASSIGNMENT

TM 11-662, chapter 3, paragraphs 15 thru 29.

RESOURCE REQUIREMENTS

Signal Subcourse SS0311

LESSON OBJECTIVES

When you complete this lesson you should be able to:

1. Explain the construction of the diode tube.

2. Explain electrostatic fields.

3. Explain space charge.

4. Explain the relationship between plate-current and plate-voltage.

5. Explain characteristic curves.

PAGES 25 THRU 50

ARE EXTRACTS FROM TM 11-662/TO 16-1-255

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

LESSON 2 - DIODES

LESSON EXERCISES

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. In a diode with an indirectly heated cathode, the element that collects the electrons is known as the

a. plate.
b. heater.
c. getter.
d. cathode.

2. The getter is a substance used to facilitate the operation of the
a. space charge.
b. evacuation process.
c. beam-forming plates.
d. electrode within an electronic tube.

3. In addition to the heater element, a duodiode tube requires a minimum of

a. two plates and two cathodes.
b. one plate and two cathodes.
c. one cathode and two plates.
d. two plates and one anode.

4. Electron flow in a diode tube is best described as the flow of electrons from the

a. plate to the cathode when the cathode is positive in respect to the plate.

b. plate to the cathode when the plate is positive in respect to the cathode.

c. cathode to the plate when the plate is positive in respect to the cathode.

d. cathode to the plate when the cathode is positive in respect to the plate.

5. What are the four important factors that control a diode's plate current?

a. Cathode temperature, emission rate, space charge, and plate potential relative to the cathode.

b. Emission rate, magnetic field intensity, electrostatic field intensity, and cathode material.

c. Space charge, emission velocity, plate potential relative to the cathode, and filament type.

d. Filament type, cathode temperature, electrostatic field strength, and electromagnetic field strength.

6. Assume that the emission of electrons is in the direction shown in B of figure 22 (TM 11-662). When does emission saturation occur?

a. When all the electrons in the space charge are attracted to the plate.

b. When an increase in cathode temperature fails to increase electron emission.

c. When the space charge becomes so dense that electron flow to the plate is cut off.

d. When an electron is supplied back to the cathode from the space charge for each electron emitted by the cathode.

7. The space charge within a diode tube is best described as a charge that

a. is constantly varying in density.

b. maintains a positive potential with respect to the cathode.

c. builds up to a point of equilibrium at which it has neither negative nor positive characteristics.

d. remains at a negative potential, regardless of whether a positive or a negative charge is applied to the plate.

8. Figure 25 of TM 11-662 shows a characteristic curve for a diode. This curve shows the relationship between the

a. plate voltage and plate current.

b. plate current and filament voltage.

c. filament current and plate voltage.

d. space charge voltage and plate current.

SITUATION

Assume that you are analyzing the characteristic curves of a diode tube to determine if the tube is acceptable as the rectifier in a power supply. The characteristic curves for the tube are shown in figures 29 and 30 in TM 11-662.

Exercises 9 through 13 are based on the above situation.

9. Curve ABC in figure 29 is relatively flat along the portion from B to C. This flattened portion of the filament voltage-plate current curve is caused by the

a. space charge in the tube.

b. secondary emission in the tube.

c. temperature saturation of the tube.

d. dynamic characteristics of the tube.

10. Point D on curve ADE in figure 29 is known as the

a. ionization point.
c. operating point.
b. saturation point.
d. cutoff point.

11. In figure 30, point A on curve ABC indicates that

a. the plate current is zero when plate voltage is zero.

b. the space charge is repelling electrons back to the cathode.

c. a small amount of filament current is added to the plate current.

d. a small amount of plate current flows when plate voltage is zero.

12. To increase the curve to give it the shape shown as the extended straight dotted line in figure 30, it is necessary to

a. increase the plate voltage.

b. raise the emitter temperature.

c. reverse the polarity of battery E_{bb}.

d. change from a directly to an indirectly heated cathode.

13. Assume that curve ABC in figure 30 is being used to determine the dc plate resistance of the diode. What is the dc plate resistance if the plate voltage is 450 volts?

a. 6,800 ohms.
c. 5,100 ohms.
b. 6,400 ohms.
d. 1,500 ohms.

14. In the characteristic curve shown in figure 32, a saturation point is not indicated. This curve illustrates the

a. theoretical action if the effects of saturation were ignored.

b. characteristics of a tube with extremely low dc plate resistance.

c. primary difference between static and dynamic characteristics of diode tubes.

d. action of an oxide-coated cathode which, for all practical circuits, has no saturation point.

15. The ac and dc resistances of a diode tube are related directly to the tube's operating potentials. The ac and dc plate resistances are related to the plate voltage in such a way that as the

a. plate voltage increases, both the ac and dc plate resistances increase.

b. plate voltage increases, both the ac and dc plate resistances decrease.

c. plate voltage decreases, the ac plate resistance decreases, and the dc plate resistance increases.

d. plate voltage decreases, the ac plate resistance increases, and the dc plate resistance decreases.

16. The plate-current plate-voltage characteristic of a certain diode is shown in figure 33 of TM 11-662. If this diode is operated with its plate voltage varying between 12 and 14 volts, the ac plate resistance of the tube will be approximately

a. 250 ohms.

b. 300 ohms.

c. 400 ohms.

d. 500 ohms.

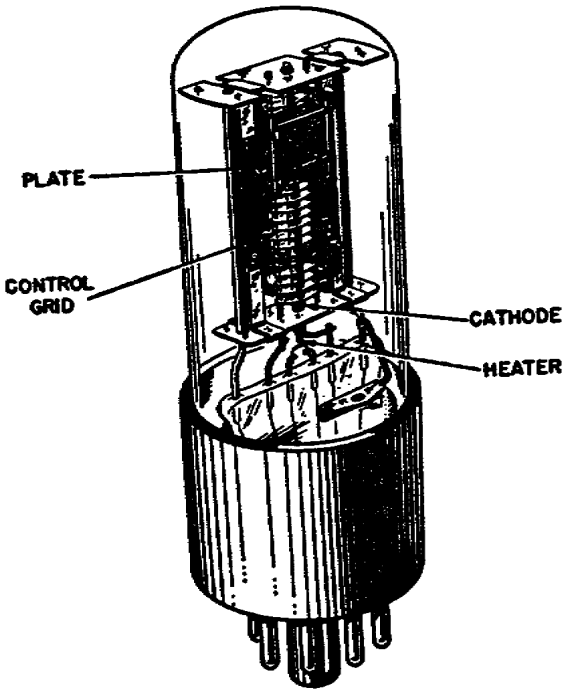
17. Both the static and the dynamic characteristic curves depict the behavior of electron tubes. The methods of obtaining the curves differ in that the dynamic curves are obtained

a. by applying ac voltages to the tubes, and the static curves are obtained by applying do voltages.

b. by applying do voltages to the tubes, and the static curves are obtained by applying ac voltages.

c. when there is NO load in the circuit, and the static curves are obtained when there is a load in the circuit.

d. when there is a load in the circuit, and the static curves are obtained when there is NO load in the circuit.



triode fundamentals

lesson three

triode fundamentals

INTRODUCTION

The remarkable achievements in the field of electrons, which includes radio, radar, television, guided missiles, etc., are a direct result of the discovery of the vacuum tube. The single greatest advance in the development of vacuum tube theory and application was the audion tube of Lee DeForest. The outstanding feature of this tube was the insertion of a third electrode in the diode that Fleming had developed. DeForest used his third electrode which was placed between the plate and the amount of electron flow. Because of the form of this control electrode in the earlier tubes, the term grid was applied to it. The grid is now defined as an electrode that contains openings through which electrons may pass. Physically, it is constructed of mesh, screen or spiral wires placed between the plate and cathode.

Many modern tubes contain more than one grid; so to describe its function as well as to differentiate it from other grids, this third electrode is called a "control grid." A tube which contains three active elements--a cathode, a control grid, and a plate--is called a "triode." In this lesson you will study the construction, operation and characteristics of the triode.

TEXT ASSIGNMENT

TM 11-662, chapter 4, paragraphs 32-44.

RESOURCE REQUIREMENTS

Signal Subcourse SS0311

LESSON OBJECTIVES

When you complete this lesson you will be able to:

1. Recognize the major elements of the triode electron tube.

2. Characterize and explain the function of the control grid.

3. Know the function of the bias voltage and potentials used.

4. Know the importance of the cutoff voltage and the effect it has on the operation of the triode.

PAGES 60 THRU 81

ARE EXTRACTS FROM TM 11-662/TO 16-1-255

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

LESSON 3 - TRIODE FUNDAMENTALS

LESSON EXERCISES

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. In addition to the two elements contained in a diode, the triode tube contains a third element that enables it to amplify signals. This third element is called a

a. grid.
b. plate.
c. cathode.
d. filament.

2. A common check on the operation of a glass electron tube is to see if the emitter is incandescent. This is often difficult in a triode because the

a. emitter is often indirectly heated.
b. plate will usually envelop the emitter surface.
c. brilliance of the getter flash hides the emitter incandescence.
d. inside of the tube envelope is covered with a deposit from the getter.

3. When a vacuum tube is being made, a getter is used to eliminate unwanted gases. The material usually used for the getter in a triode tube is

a. molybdenum.
b. magnesium.
c. nichrome.
d. tungsten.

4. To operate properly, a triode requires three different supply voltages: an A-supply, a B-supply, and a C-supply. The functions of the A-, B-, and C-voltages are to supply, respectively, the

a. filament, grid, and plate voltages.

b. plate, grid, and filament voltages.

c. grid, filament, and plate voltages.

d. filament, plate, and grid voltages.

5. The basic triode amplifier circuit shown in figure 50 (TM 11-662) can be divided into three basic systems: the input circuit, the cathode circuit, and the output circuit. The output circuit includes circuit elements between the

a. plate and ground.

b. grid and cathode.

c. grid and ground.

d. plate and grid.

6. The control grid in a triode tube normally governs the flow of plate current by

a. preventing a space charge from being established.

b. changing the distance between the wires of the helix.

c. producing an electrostatic field which controls the effect of the plate's electrostatic field.

d. attracting a definite portion of the emitted electrons to control the number of electrons reaching the plate.

7. A very small voltage on the control grid can overcome the effect of a large plate voltage. This effect, which enables the control grid to control plate current, arises from the fact that the

a. distance between the grid and cathode is much smaller than the distance between the plate and cathode.

b. plate's electrostatic field is perpendicular to the control grid's electrostatic field.

c. control grid can completely eliminate the space charge.

d. majority of grids are wound into a helix-like shape.

8. When applied to the grid, the voltage that reduces the plate current to zero is known as the

a. bias voltage.
c. cutoff voltage.

b. zero voltage.
d. saturation voltage.

9. Figure 51 of TM 11-662 shows a triode circuit and a characteristic curve for the triode. If the grid voltage on this triode is changed from -2.5 volts to +0.5 volt, the plate current (as indicated by the ammeter) will change from 15 mA to approximately

a. 0 mA.
c. 40 mA.

b. 32 mA.
d. 54 mA.

10. A dc voltage usually is applied to the control grid of a triode tube to prevent the grid from becoming positive and drawing current. This voltage is termed

a. bias voltage.
c. limiter voltage.

b. cutoff voltage.
d. saturation voltage.

11. To maintain a continuously negative potential on the control grid of a triode when the signal voltage is 14 volts peak to peak, the minimum grid bias that can be used is

a. -8 volts.
b. -11 volts.
c. -15 volts.
d. -29 volts.

NOTE: A 14-volt peak-to-peak signal is one that varies between the limits of +7 volts and -7 volts.

12. The conventional symbol used to indicate the value of dc grid-bias voltage is

a. e_b.
b. e_c.
c. E_{bb}.
d. E_{cc}.

13. In a grid family of static characteristic curves, the individual curves indicate a constant value of

a. grid voltage.
b. plate voltage.
c. grid current.
d. plate current.

14. Figure 51 of TM 11-662 illustrates a static plate-current grid-voltage characteristic. The word "static" indicates that the data for the curve was obtained

a. by using a constant grid voltage.
b. under "interference-free" conditions.
c. without a load resistor in the plate circuit.
d. without changing any of the circuit parameters.

15. Plate-current saturation is the point at which all electrons emitted by the cathode are attracted to the plate and the grid. Further positive increases in grid voltage will not increase the plate current. This condition can be avoided if the tube's emitter is

a. oxide-coated.
b. directly heated.
c. made of tungsten.
d. indirectly heated.

16. As grid voltage is made increasingly positive; plate current will increase to a certain point. This point occurs when the

a. grid current exceeds the plate current.

b. positive potential on the grid can no longer be increased.

c. emitted electrons are divided between the plate and the grid.

d. grid's electrostatic field opposes the plate's electrostatic field.

17. A grid family of characteristic curves for a 6J5 is shown in figure 53 of TM 11-662. If a 6J5 has plate voltage of 200 volts, what is the minimum voltage that can be applied to the grid of this triode so that no plate current will flow?

a. -12.6 volts
c. -15.5 volts

b. -13.5 volts
d. -18.0 volts

18. When the bias voltage applied to a 6J5 triode tube is maintained at -8 volts and the plate voltage is increased from 200 to 250 volts, the plate current will increase approximately

a. 3.4 mA.
c. 6.7 mA.

b. 5.5 mA.
d. 8.9 mA.

19. Point B on the 200-volt plate-voltage curve (fig. 53) corresponds to a current of 2.1 mA with a negative grid voltage of 9 volts. If the plate voltage is increased to 250 volts, the grid voltage needed to keep the plate current constant at 2.1 mA is approximately

a. -9.5 volts.
c. -12.6 volts.

b. -11.6 volts.
d. -15.5 volts.

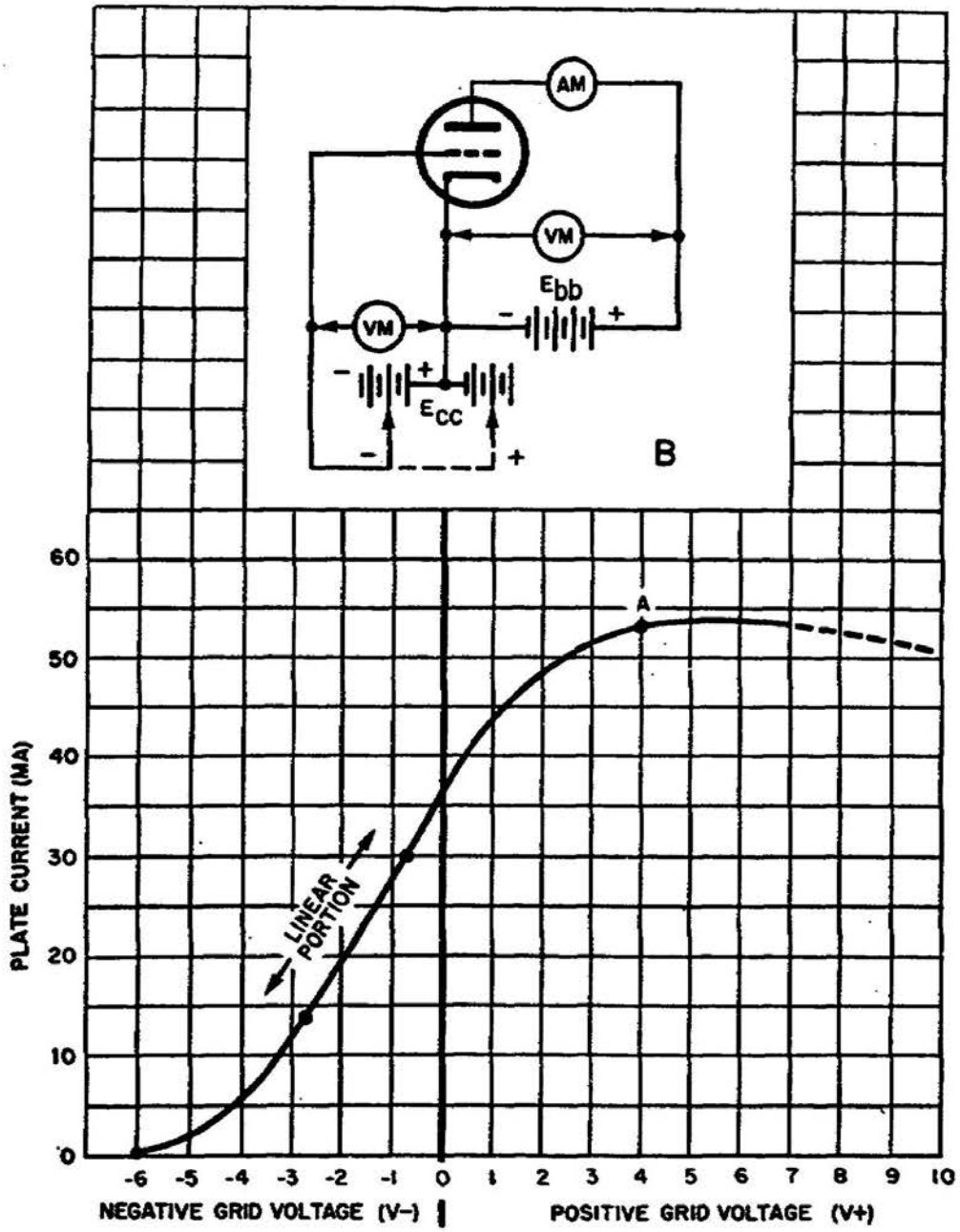
20. The operating potentials of a tube must be adjusted so that conduction takes place in the proper operating regions of the characteristic curves. Selecting an operating point for a triode on the straight portion of the characteristic curves will provide

a. a change in grid current that is inversely proportional to a change in plate current.

b. the correct cathode temperature for proper thermionic emission.

c. a change in plate current that is proportional to a change in grid potential.

d. the smallest change in plate current with a given change in grid potential.



triode characteristics

lesson four

triode characteristics

INTRODUCTION

The behavior of the plate current in a triode (or in any vacuum tube that contains three or more elements), under the influence of different control-grid and plate voltages, does not occur at random. It is a function of the tube design--specifically, the geometric organization of the tube electrodes. Examples of these are the separation between the electrodes, shape and dimensions of the electrodes and other physical details. It is these factors that determine the maximum voltages that can be applied to the electrodes, the maximum plate current permissible through the tube, the conditions for plate cutoff, and other similar facts. All of these are expressed by a group of numbers referred to as tube "constants."

Tube constants differ from tube characteristics. Whereas the characteristic is a graphical representation of tube behavior under the particular set of conditions shown, the tube constants are individual numerical ratings predicated upon the geometry of the tube. Tubes possessing similar relationships, although the specific values of grid voltage, plate voltage, and plate current necessary to make the tube perform properly may be different for the various tubes. The three primary tube constants are amplification factor, ac plate resistance and transconductance which will be discussed in this lesson.

TEXT ASSIGNMENTS

1. Attached Memorandum, paragraphs 3-1 thru 3-9.

2. TM 11-662, chapter 4, paragraphs 45-57

NOTE: Study the attached memorandum before studying the TM references.

RESOURCE REQUIREMENTS

Signal Subcourse SS0311

LESSON OBJECTIVES

When you complete this lesson, you should be able to:

1. Define tube constants and know how tube constants affect the electron-tube circuit.

2. Calculate the amplification factor, ac plate resistance, and transconductance of an electron-tube circuit.

3. State the purpose and use of the load line and how the load line affects the electron-tube circuit.

4. State the purpose and use of a tube tester, and know how to make and interpret tube measurements.

ATTACHED MEMORANDUM

Section I. PEAK-TO-PEAK VOLTAGE

3-1. SINE WAVE SIGNAL VOLTAGES

The magnitude of a sine wave signal voltage can be specified by giving its peak-to-peak value. This method of describing the magnitude of a sine wave voltage specifies the difference in potential between the signal's positive and negative voltage peaks. For example, the sine wave voltage shown in figure 3-1 of this lesson booklet swings 3 volts in a positive direction and 3 volts in a negative direction. There is a 6-volt difference in magnitude between the positive and negative peaks. The alternating voltage in figure 3-1 is therefore referred to as being a 6-volt peak-to-peak signal.

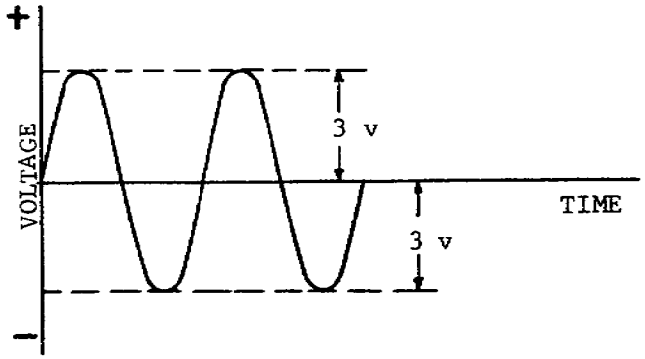


Figure 3-1. A 6-volt peak-to-peak sine wave voltage.

3-2. DISTORTED SINE WAVES

If a sine wave voltage is distorted, i.e., if it does not swing to an equal peak in both the positive and negative direction, then a single peak reference, such as 6 volts peak to peak, does not fully describe the signal. To avoid this limitation in the use of the peak-to-peak designation, this definition is made: any peak-to-peak voltage mentioned in this subcourse is assumed to be an undistorted sine wave swinging to an equal peak magnitude in both the positive and negative directions.

Section II. TUBE TESTERS

3-3. GENERAL OPERATION

Tube testers, in general, provide a means of applying typical operating voltages to the tube that is being tested. By providing a number of sockets or by adjusting several switches and potentiometers, a typical filament voltage, grid voltage, or plate voltage is applied to the tube. The tube can then be given various tests in this "typical" environment. Obviously, if the tube is to be used in an application where it is not being operated with these "typical" operating voltages, the tube tester will not be likely to give an accurate indication of the tube's condition.

3-4. GASSY TUBES

If a tube is gassy (that is, if the tube's vacuum is low or absent because of insufficient evacuation or the release of gasses imbedded in the electrode metals), grid current will flow in spite of negative grid bias. Thus, a milliammeter or microammeter in the grid circuit can be used to determine whether a tube is gassy. If a current is detected when a tube's grid is negatively biased, then that tube is gassy.

3-5. TRANSCONDUCTANCE TEST

Figure 3-2 illustrates a typical circuit used in making a transconductance test. Recommended operating voltages (E_g, E_f, E_{bb} etc.) are applied to the tube and a 1-volt rms signal is applied to the grid. The ac component of the resulting plate current is indicated by the ac milliammeter. The transformer in the plate circuit isolates the milliammeter so that it is not deflected by the dc component of plate current. The transconductance is then equal to the milliammeter

reading (an rms reading) multiplied by 1000 $\left(g_m = \frac{i_b}{e_g}\right)$.

For example, if the plate milliammeter reads 3-mA rms, the tube's transconductance is 3 x 1000 = 3000 micromhos. The complete calculation is:

$$g_m = \frac{i_b}{e_g} = \frac{3\ \text{mA}}{1\ \text{volt}} = \frac{3 \times 10^{-3}\ \text{amp}}{1\ \text{volt}} = 3 \times 10^{-3}\ \text{mhos}$$

$$= 3{,}000 \times 10^{-6}\ \text{mhos}$$

$$= 3{,}000\ \text{micromhos.}$$

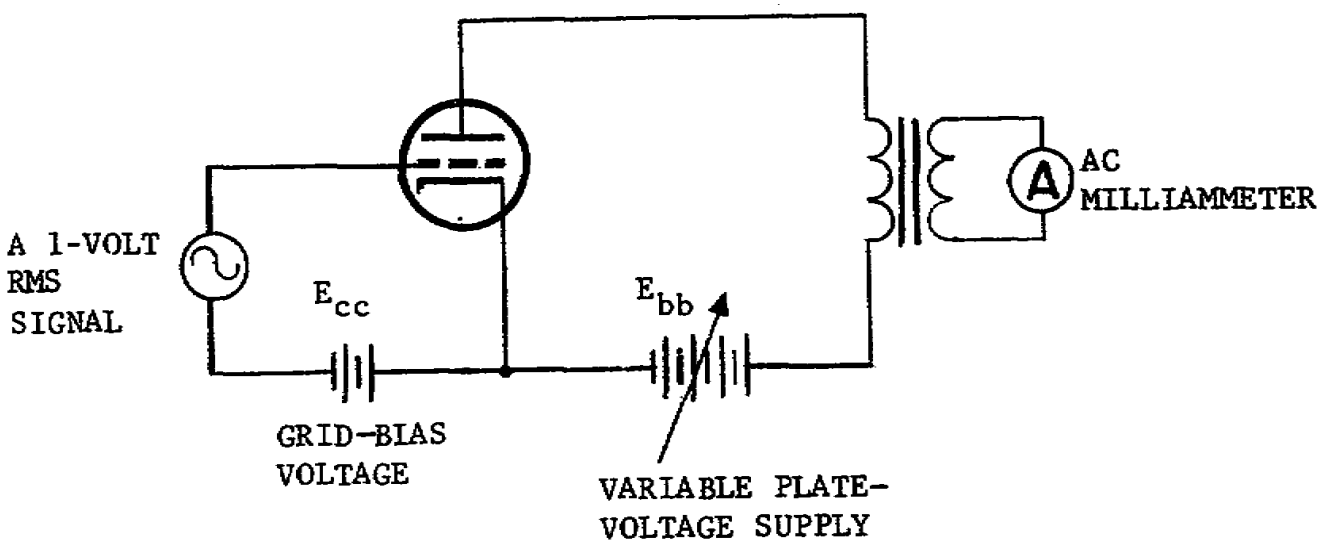


Figure 3-2. A circuit for a transconductance test.

3-6. EMISSION TEST

An emission test is generally made by a circuit of the form shown in figure 3-3 below. Rated filament voltage is utilized and a reasonable value of voltage is applied to the plate electrode. The milliammeter indicates whether the cathode is emitting properly. The various remaining electrodes (control grid, screen grid, etc.) are, by means of switches, attached to the plate, one at a time. Failure of the current to increase when a given electrode is connected is an indication that that particular electrode is open-circuited.

3-7. SHORT TESTS

Occasionally a short circuit develops between electrodes in a tube. A test for this condition consists merely in applying a voltage across the two suspected electrodes. A device to

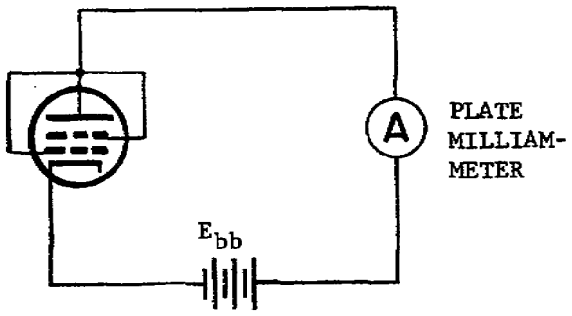


Figure 3-3. A circuit for an emission test.

detect current flow (a meter or neon lamp) in series with the voltage source will then indicate whether a short exists. Switches on the tube tester allow connection of the voltage source across any two suspected electrodes.

3-8. FILAMENT CONTINUITY TEST

Frequently a tube's filament burns out, leaving an open circuit between the filament electrodes. A filament continuity test is performed in the same manner as a short test. A voltage source is connected across the filament electrode, and current flow indicates the filament is "good," that is, not open-circuited.

3-9. USING A TUBE TESTER

Most tube testers will perform a variation of some or all of the tests discussed. The transconductance (g_m) and emission tests are the basic tests performed on most tube testers. It should be remembered, however, that a tube tester only provides an estimate of the condition of a tube. Many tubes will pass all tube tester tests and yet not operate properly in a certain circuit. The ultimate check on a tube's operation is to ascertain whether is does its job in the circuit in which it is said to be used.

PAGES 95 THRU 121

ARE EXTRACTS FROM TM 11-662/TO 16-1-255

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

LESSON EXERCISES

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. Assume that a 0.2-volt change in the grid voltage on a certain triode causes exactly the same change in plate current as does a 4.0-volt change in plate voltage. The amplification factor (μ) of this triode is

a. 2.
c. 20.
b. 4.
d. 40.

2. Assume that a certain tube's plate current increases from 4 mA to 5 mA when the grid voltage, E_{CC} , changes by 0.5 volt. If plate voltage must be decreased 30 volts to return the plate current to 4 mA, the tube's amplification factor (μ) is approximately

a. 4.
c. 30.
b. 15.
d. 60.

SITUATION

Figure 3-4 below shows a triode circuit and a graph of the plate characteristics of the triode. The operating point of the triode is indicated on the characteristics by point Q. At point Q, the plate current is 7.0 mA and plate voltage is 210 volts.

Exercises 3 through 7 are based on the above situation.

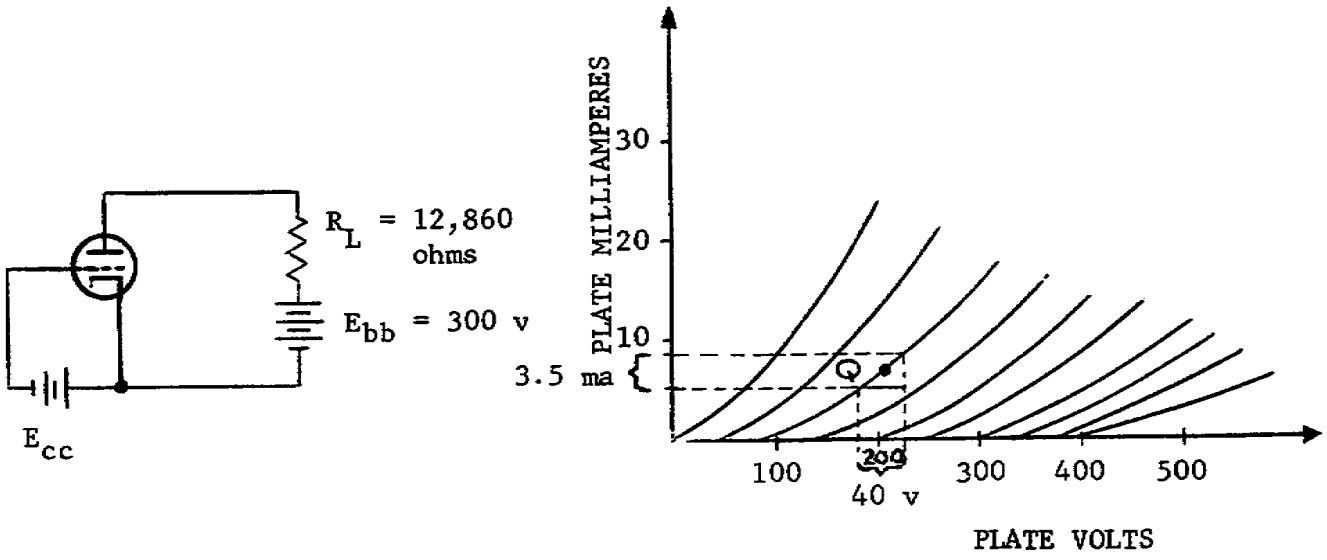


Figure 3-4. A basic triode circuit and plate characteristics.

3. At the quiescent conditions indicated by point Q, the do resistance of the triode R_p is

a. 10K.

b. 15K.

c. 21K.

d. 30K.

4. The ac resistance, r_p , of the tube describes the opposition the tube presents to small changes in plate current. The resistance offered by this tube to small changes around point Q is approximately

a. 3.5K.

b. 7.0K.

c. 11.4K.

d. 14.0K

NOTE: Use the changes shown in figure 3-4.

5. If the tube is operating at point Q, (fig. 3-4) and no signal is applied to the grid, what is the voltage drop across the load resistor?

a. 40 volts

b. 90 volts

c. 140 volts

d. 210 volts

6. If the grid-bias voltage, E_{CC} increases to a value so that the tube is cut off, the voltage drop across R_L will be equal to

a. zero.

b. -20 volts.

c. 150 volts.

d. 300 volts.

7. If you draw the circuit load line on the plate characteristics graph, at what point will it intersect the plate voltage axis?

a. 90 volts

b. 150 volts

c. 210 volts

d. 300 volts

8. Assume that you do not have the characteristic curves for a certain tube but you know that is has an r_p of 9,000 ohms and a g_m of 3,000 micromhos. You can calculate that this tube's amplification factor is

a. 27.

b. 30.

c. 270.

d. 300.

Exercises 9 through 13 are based on figure 3-5 below.

9. The point on the load line that corresponds to the quiescent conditions in the circuit of part A in figure 3-5 is point

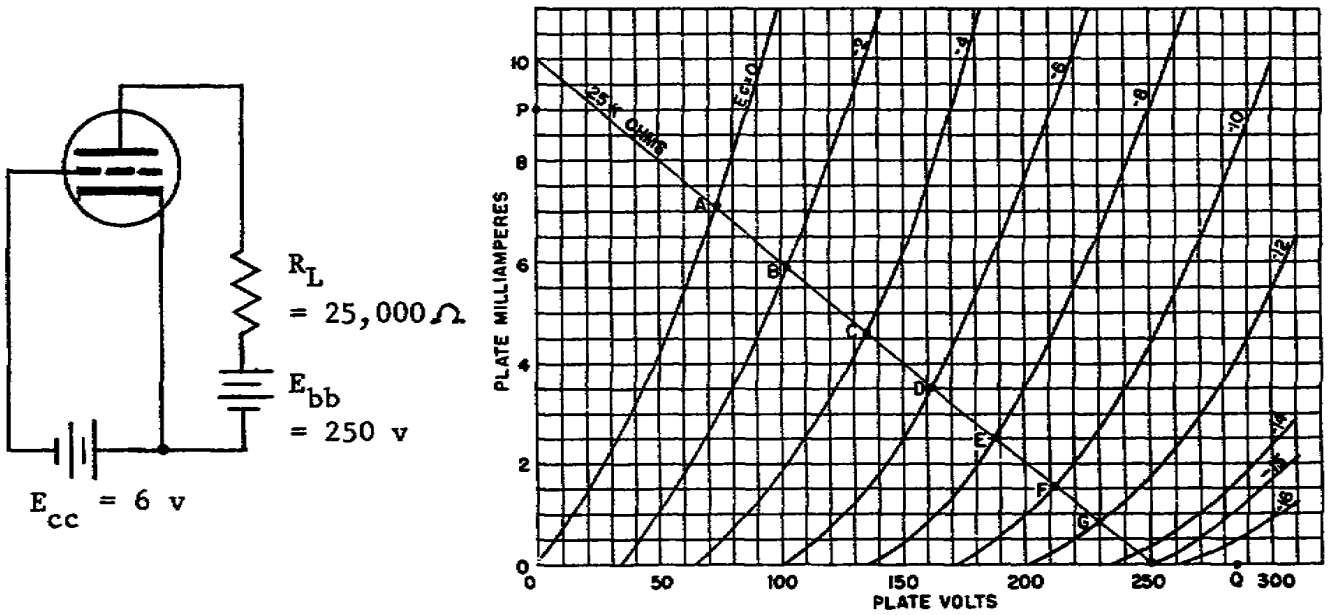
a. B. c. D.

b. C. d. E.

10. If the grid-bias voltage is momentarily changed to −4 volts, the current flowing in the plate circuit will momentarily increase to

a. 3.5 mA. c. 4.6 mA.

b. 4.1 mA. d. 5.8 mA.



PART A. THE TRIODE CIRCUIT

PART B. THE TRIODE'S PLATE CHARACTERISTICS WITH LOAD LINE

Figure 3-5. Analyzing the basic triode circuit.

11. Assume that an 8-volt peak-to-peak signal is applied to the grid circuit in the manner shown in figure 64 (TM 11-662). The point of operation on the load line will then vary between points

a. A and C.
c. B and E.

b. A and G.
d. B and F.

12. Assume that a 12-volt peak-to-peak voltage is applied to the grid circuit in the manner illustrated in figure 64 of TM 11-662. The load line shows that when the signal voltage swings 6 volts positive the plate current increases by 3.6 mA, and when the signal voltage swings 6 volts negative the plate current decreases by 2.7 mA. The fact that equal changes in grid voltage cause different changes in plate current shows that the

a. tube is defective.

b. output will be slightly distorted.

c. control-grid bias is not functioning properly.

d. interelectrode capacitances will be abnormally high.

13. If the load resistor is changed to 50K, the orientation of the load line will change. However, the load line still intersects the plate voltage axis at 250 volts, but will intersect the plate current axis at

a. 2 mA.
c. 10 mA.

b. 5 mA.
d. 15 mA.

14. As a circuit's load resistance is changed, there is a significant effect upon the linearity of the dynamic transfer characteristic and, therefore, upon the distortion. What effect will an increase in the load resistance have on the transfer characteristic and the distortion?

a. The transfer characteristic becomes straighter and, therefore, the distortion decreases.

b. The transfer characteristic becomes straighter and, therefore, the distortion increases.

c. The transfer characteristic becomes more curved and, therefore, the distortion decreases.

d. The transfer characteristic becomes more curved and, therefore, the distortion increases.

15. Figure 3-6 below illustrates the dynamic transfer characteristic for a certain triode circuit. If, in this circuit, E_{CC} = -3 volts, then the operating point (point of quiescent conditions) on the transfer characteristic will be point

a. A.

b. B.

c. C.

d. D.

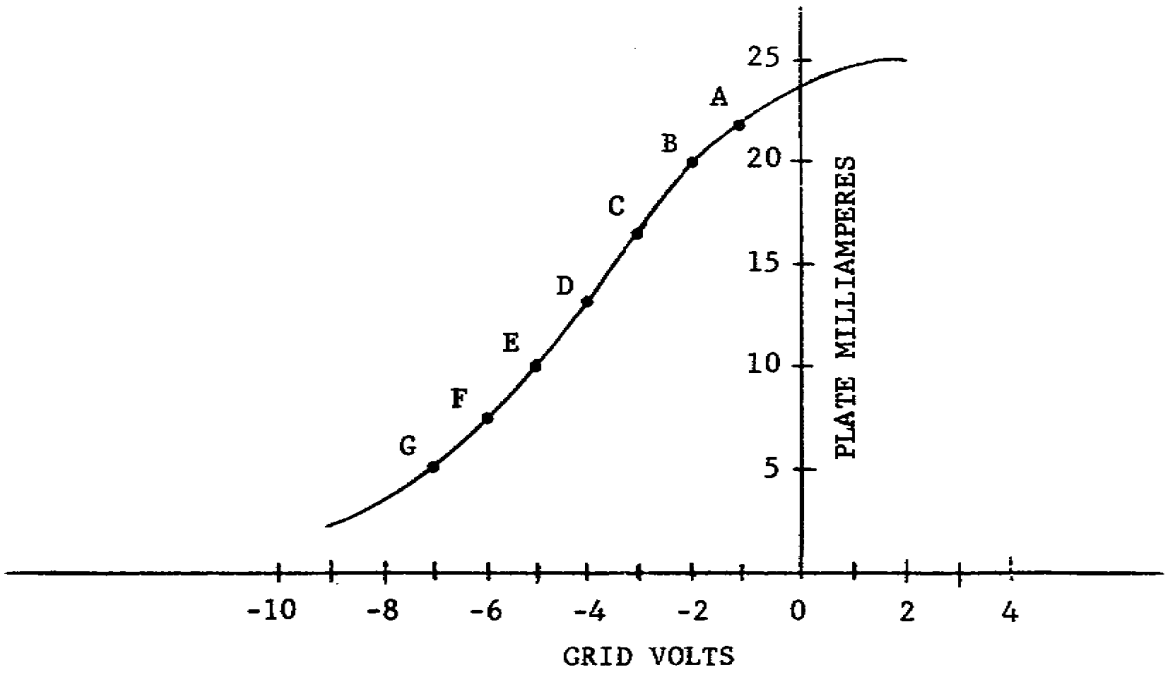


Figure 3-6. A dynamic transfer characteristic curve.

16. Assume that point D is the operating point on the transfer characteristic in figure 3-6, and a 6-volt peak-to-peak signal is applied to the grid. The plate current will then vary between the limits of

a. 5 and 22 mA.

c. 7 and 20 mA.

b. 7 and 13 mA.

d. 13 and 22 mA.

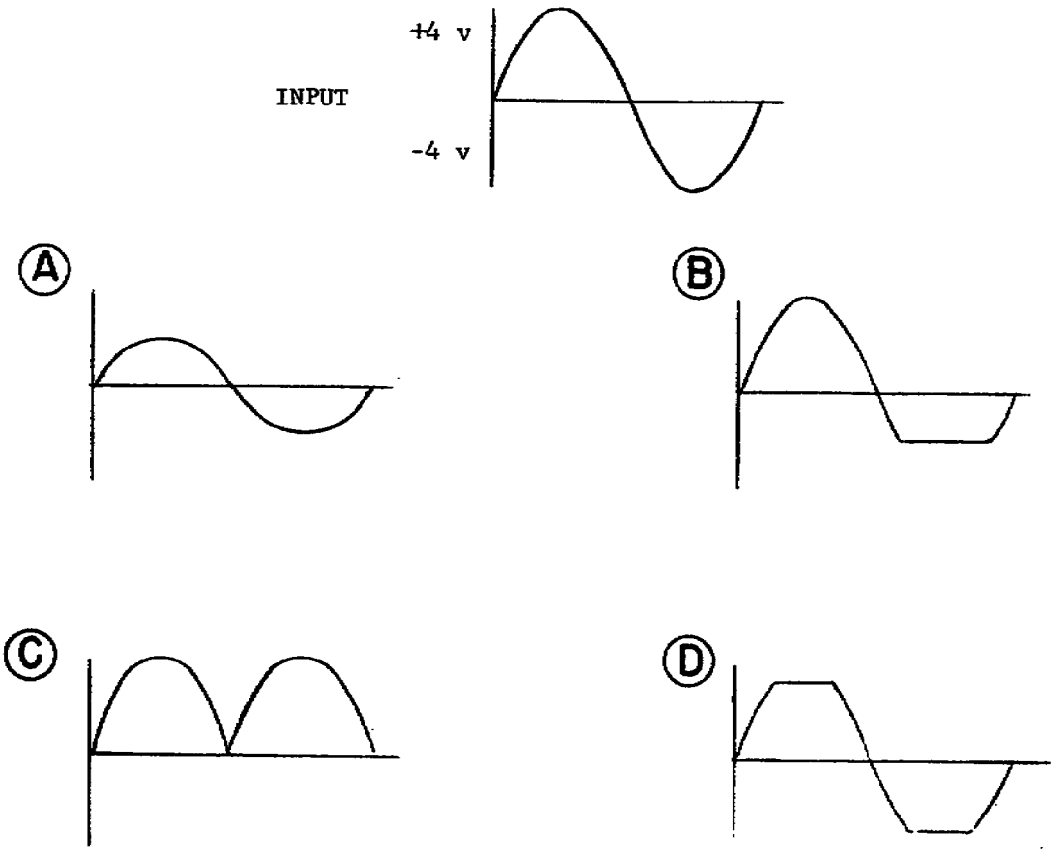
17. Assume that you are using the dynamic transfer characteristic in figure 3-6 to determine the plate-current waveform for a triode circuit biased at -7 volts (point G). If the input signal shown in figure 3-7 is applied to the grid, the plate-current waveform will be most like the waveform shown in figure 3-7 in the sketch labeled.

a. A.

c. C.

b. B.

d. D.



18. The interelectrode capacitance existing between a tube's control grid and its cathode is designated by the symbol

a. C_{pk}.

b. C_{gk}.

c. $C_{g}p$.

d. C_{cgc}.

19. Interelectrode capacitance in an electron tube should be kept as low as possible. A high grid-to-plate capacitance is undesirable in a triode because it

a. neutralizes the feedback action.

b. minimizes the possibility of oscillation.

c. results in harmful interaction between the control grid circuit and the plate circuit.

d. causes distortion by introducing serious curvature in the circuit's dynamic transfer characteristic.

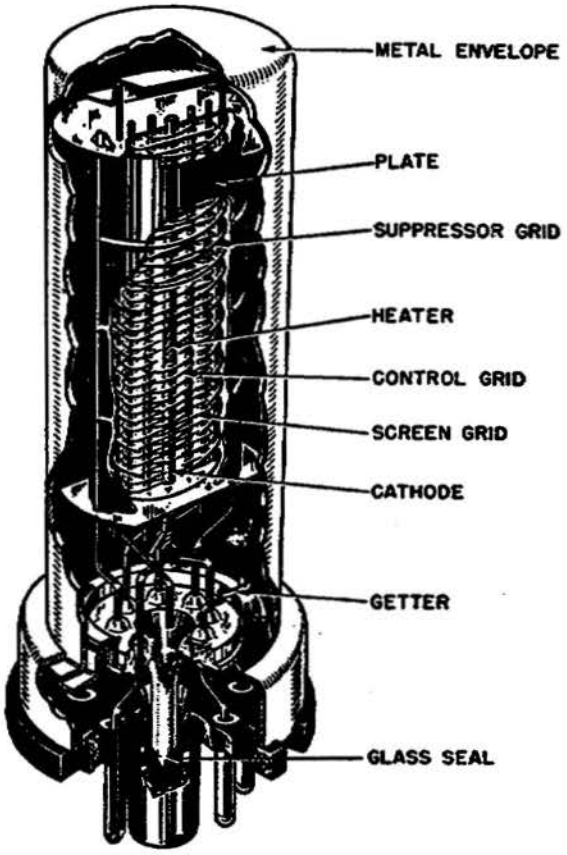
20. Assume that the proper adjustments for a transconductance measurement have been made in the circuit shown in figure 3-2 of this lesson booklet. If the plate milliammeter indicates a 4.5-mA (rms) plate current, the tube's transconductance is

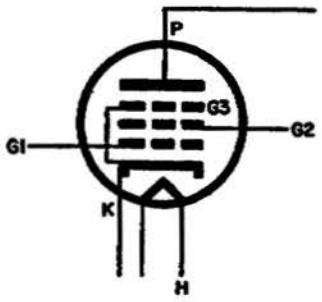
a. 3,500 micromhos.

b. 4,000 micromhos.

c. 4,500 micromhos.

d. 5,000 micromhos.





multielement tubes

lesson five

multielement tubes

INTRODUCTION

Early in the history of tube development and application, tubes were designed for general service. That is, one type of tube, the triode, was used for many varied applications. Obviously, this one tube could not meet every possible requirement and do it effectively.

Present trends in tube design are the development of "specialty" type tubes. These tubes are designed either to give optimum performance in a particular application; or to combine in one vacuum envelope functions which required two or more tubes.

The construction and theory of operation of these multi-electrode tubes will be discussed in this lesson.

TEXT ASSIGNMENT

TM 11-662, chapter 5, paragraphs 60-74

RESOURCE REQUIREMENTS

Signal Subcourse SS0311

LESSON OBJECTIVES

When you have completed this lesson you should:

1. Know the function of the screen grids and the effects they have on the tetrode and pentode tubes.

2. Be able to explain the function of the suppressor grid and the effects of its secondary emission in pentode tubes.

3. Know the theory and application of beam power tubes.

4. Know the function of the different types of multigrid tubes.

PAGES 132 THRU 157

ARE EXTRACTS FROM TM 11-662/TO 16-1-255

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

LESSON 5 - MULTIELEMENT TUBES

LESSON EXERCISES

In each of the following exercises, select the ONE answer that BEST completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. The tetrode and pentode tube types often are used in place of the triode at frequencies between the audio and microwave ranges. In general, the triode requires neutralizing circuits at high frequencies because the

   a. interelectrode capacitance couples an undesirable feedback from the output circuit back to the input circuit.

   b. secondary emission creates a negative resistance region in the tube's transfer characteristic.

   c. single control grid cannot withstand the high frequency plate current.

   d. amplification factor is often too large for high-frequency applications.

2. A fourth electrode, called the screen grid, exists in a tetrode, which is not found in a triode. The purpose of the screen grid is to

   a. act as an electrostatic shield between the control grid and the plate, thus reducing Cgp .

   b. shield the control grid from the effects of secondary emission.

   c. supplement the controlling action of the control grid.

   d. collect electrons that do not reach the plate.

3. The control grid or plate electrode is sometimes connected to a cap on the top of an electron tube. The reason for this practice is to

a. allow visual examination of the electrode.

b. allow that particular electrode to dissipate its heat.

c. provide an electrode that will collect the spurious electrons rising to the top of the tube.

d. provide physical separation of the control grid and plate electrodes in order to minimize grid-to-plate capacitance.

SITUATION

Figure 4-1 shows a tetrode circuit and the plate characteristic for the tetrode.

Exercises 4 through 8 are based on this situation.

4. Note the four points: A, B, C and D, in part A of figure 4-1. The input of the tube in this circuit is between points

a. A and C.

b. B and C.

c. B and D.

d. C and D.

5. What is the value of the screen grid voltage, E_{C2}?

a. 100 volts.

b. 150 volts.

c. 200 volts.

d. 250 volts.

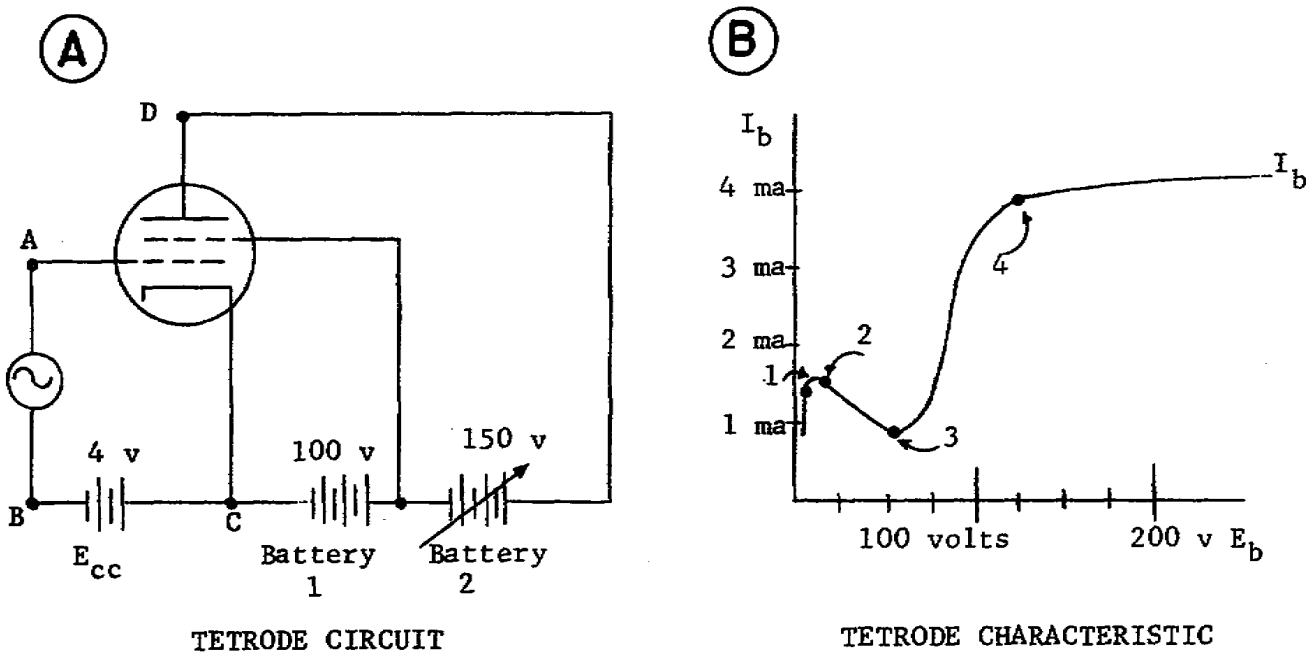


Figure 4-1. A tetrode circuit and characteristic.

6. If the plate voltage in a tetrode circuit is kept greater than a certain minimum value, large variations in plate voltage will have little effect on the value of plate current. In this circuit, this minimum value of plate voltage is approximately

a. 5 volts.

b. 50 volts.

c. 100 volts.

d. 125 volts.

7. The plate characteristic curve shown in part B of figure 4-1 illustrates how plate current varies with plate voltage. In the region between points 3 and 4, both plate current and screen current are changed by a change in plate voltage; that is, an increase in plate voltage will cause

a. a decrease in plate current and a decrease in screen current.

b. a decrease in plate current and an increase in screen current.

c. an increase in plate current and a decrease in screen current.

d. an increase in plate current and an increase in screen current.

8. The plate characteristics of a tetrode are said to have a region of negative resistance or a region in which a decrease in plate voltage will cause an increase in plate current or vice versa. This region is noted on the characteristic of part B (fig. 4-1) between points

a. 1 and 2.

b. 2 and 3.

c. 2 and 4.

d. 3 and 4.

9. Negative resistance effects are greatly reduced in modern tetrode tubes. This has been accomplished by

a. improvements in plate material.

b. use of isolating top cap connections.

c. nonuniform design of the control grid.

d. overlapping design of the grids within the tube.

10. The purpose of the suppressor grid in a pentode is to suppress the effects of

a. secondary emission.

b. high plate resistance.

c. plate-current saturation.

d. cathode-to-plate capacitance.

11. When a pentode is used with a high load resistance, the transfer characteristic develops a sharp "knee." This can be a disadvantage, because when such curvature in the transfer characteristic is near the operating point, it indicates the presence of

a. abnormally high transconductance.

b. high grid-to-plate capacitance.

c. secondary emission effects.

d. distortion.

12. A comparison of the two methods of aligning the screen and control grids (fig. 82 of TM 11-662) shows that method B allows more electrons to reach the plate. Another advantage gained by aligning the grids by using method B is

a. an increase in screen current.

b. a reduction in plate resistance.

c. an increase in the amplification factor.

d. a reduction in the effects of secondary emission.

13. Consider the effect of the plate voltage, the screen voltage, the control grid bias, and the plate load resistance on a pentode's transconductance rating. Which of these four can be changed without affecting the transconductance?

a. The plate voltage

b. The screen voltage

c. The control grid bias

d. The plate load resistance

14. The beam-forming plates in a beam power tube create an electric plane called the virtual cathode. The purpose of this virtual cathode is to

a. repel the secondary electrons emitted from the plate.

b. repel the electrons emitted from the actual cathode.

c. increase the plate resistance of the tube.

d. increase the screen current.

15. If a pentode's screen and suppressor grid leads are connected to the plate lead, the pentode's characteristics will more closely resemble those of a

a. diode.

b. triode.

c. tetrode.

d. beam power tube.

16. Assume that, as an experiment, you rewind the wires of the control grid of a pentode so as to make it a variable-μ pentode. How will this "new" tube differ in its operation from one with a conventional control grid?

a. The plate current will become independent of plate voltage at lower plate potentials.

b. The plate resistance will increase at low values of grid bias.

c. The grid-bias cutoff voltage will be greater.

d. The grid current will increase.

17. The suppressor grid in a pentode is located between the

a. control grid and the screen grid.

b. cathode and the control grid.

c. screen grid and the plate.

d. screen and the cathode.

18. The pentode tube element that performs approximately the same function as the beam-forming plates in a beam power tube is called a

a. plate.
b. cathode.
c. screen grid.
d. suppressor grid.

19. The pentagrid converter tube shown in figure 90 of TM 11-662 is a heptode that can be considered to be made up of two smaller tubes. These two tubes are a

a. pentode and a diode.

b. pentode and a hexode.

c. triode and tetrode.

d. triode and a beam power tube.

20. A multiunit tube houses the electrodes for two or more tubes inside one envelope. Of the four multiunit tube symbols shown in figure 4-2, which is the symbol for a triode-pentode tube?

a. A
b. B
c. C
d. D

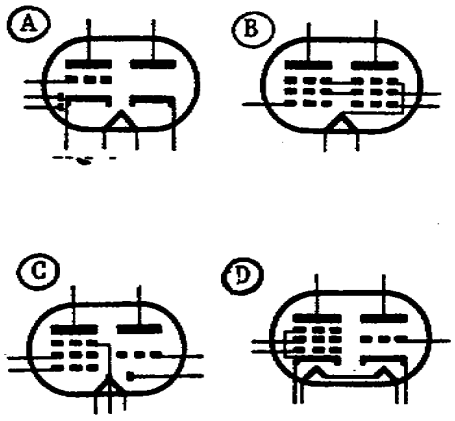


Figure 4-2. Four multiunit tube symbols.

HOLD ALL TEXTS AND MATERIALS FOR USE WITH EXAMINATION AND SS0312.

LESSON SOLUTIONS

SIGNAL SUBCOURSE SS0311..... ELECTRON TUBES

Lesson 1..... .Electron Emission

All references are to TM 11-662

1. d - para 5a

2. c - para 4c

3. a - para 6f

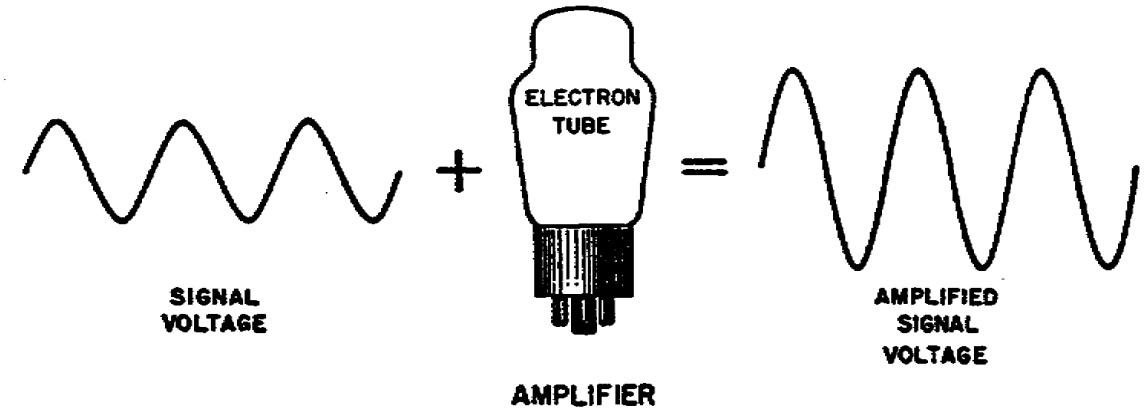
4. c - para 3g

5. c - para 5e

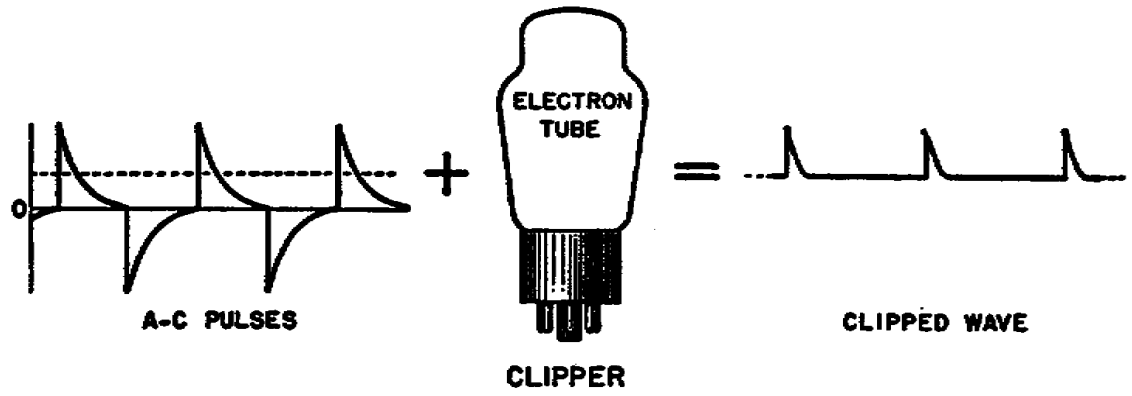
6. d - para 6e

7. a - para 4b

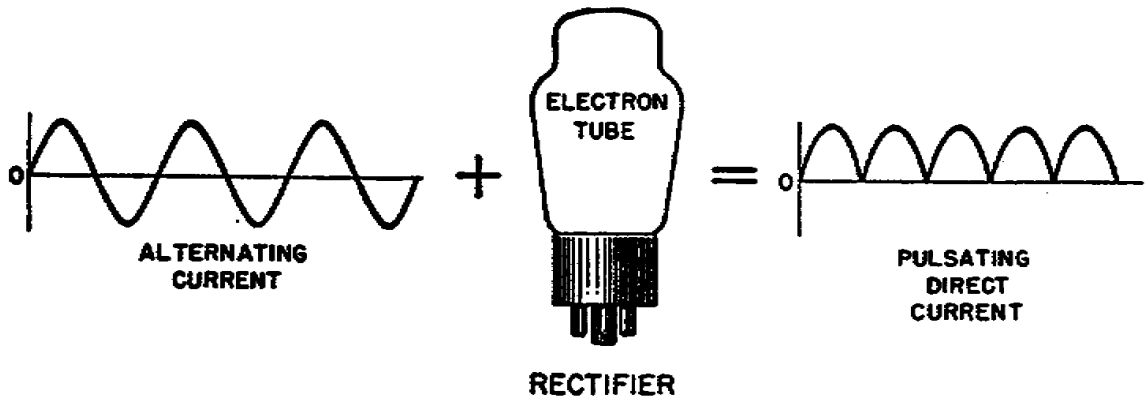
8. para 5b



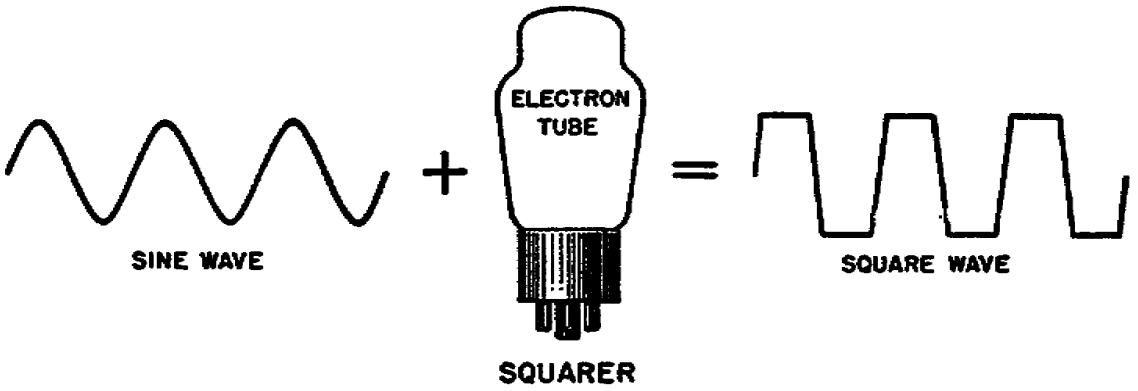
9. para 5d



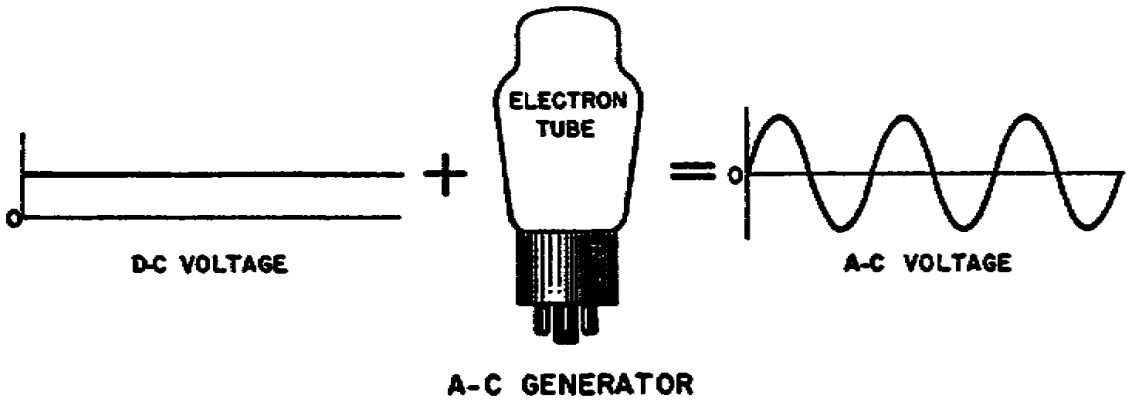
10. para 5a



11. para 5b



12. para 5c



13. d -- para 3c, d

14. b -- para 5b

15. c -- para 3e

16. c -- para 8a, 9b

17. d -- para 11, 11b

18. a -- para 12a

Lesson 2..... Diodes

All references are to TM 11-662.

1. a -- para 15b

2. b -- para 15j

3. c -- para 15i; fig. 19

4. c -- para 16m

5. a -- para 17b

6. d -- para 17h

7. d -- para 17k

8. a -- para 18h; fig. 25

9. a -- para 22c

10. b -- para 22d

11. d -- para 23c

12. b -- para 23d

13. b -- para 24d

In figure 30, a plate voltage of 450 volts causes a plate current of 70 milliamperes. Therefore, the dc plate resistance is

$R_p = E_b/I_b$ = 450 volts/70 mA = 450/0.07 = 6,400 ohms.

14. d -- para 24h

15. b -- para 24f, 25f

16. c -- para 25d

$$\text{ac plate resistance} = \frac{\text{change in } e_p}{\text{change in } i_p} = \frac{14 - 12}{23 - 18} = \frac{2 \text{ volts}}{5 \text{ mA}}$$

ac plate resistance = 400 ohms.

17. d -- para 26a

Lesson 3..... Triode Fundamentals

All references are to TM 11-662.

1. a -- para 32a, e(7)

2. d -- para 32b(3)

3. b -- para 32b(3)

4. d -- para 32f; fig. 41

5. a -- para 33b(1); fig. 42

6. c -- para 35b, d; fig. 45

7. a -- para 35e(1)

8. c -- para 35e(3)

9. c -- para 42d(2)

10. a -- para 39b; fig. 48

11. a -- para 39c

With a 14-volt peak-to-peak signal, the maximum positive swing of signal voltage will be 7 volts. Therefore, a fixed bias of minus 8 volts will maintain the grid at a negative value.

12. d -- para 41b(4)

13. b -- para 42b, 43a

14. c -- para 42c(2)

15. a -- para 42g(1)

16. c -- para 42f(1)

17. a - para 43d(1); fig. 53

18. b -- para 43d(2), (3); fig. 53

On the 200-volt plate voltage curve, a current of 3.4 mA is seen to correspond to a grid voltage of -8 volts. When the plate voltage is increased to 250 volts, the 250-volt curve shows a plate current of 8.9 mA corresponding to a grid voltage of -8 volts. Thus the increase in plate current is:

8.9 - 3.4 = 5.5 mA.

19. b -- para 43d(3)

20. c -- para 43e

Lesson 4.....Triode Characteristics and Constants

All references are to TM 11-662, unless otherwise indicated.

1. c -- para 46a

$$\text{Amplification Factor} = \frac{\text{small change in plate voltage}}{\text{small change in grid voltage}} = \frac{4.0}{0.2} = 20$$

2. d -- para 46a

A change of 30 volts in plate voltage results in the same change in plate current as a 0.5-volt change in grid voltage. The ratio of these small changes in voltage is

$$\text{amplification factor, } (\quad) = \frac{e_b}{e_g} = \frac{30}{0.5} = 60$$

3. d -- para 48b

The dc resistance is determined by applying Ohm's Law, where the numerator is the steady voltage at the plate, e_b 210 volts, and the denominator is the corresponding steady plate current, I_b = 7.0 mA.

$$R_p = \frac{210V}{7.0\ mA} = \frac{210}{.007} = 30K$$

4. c -- para 48c; Attached Memorandum, fig. 3-4

The construction on the plate characteristics of figure 3-4 shows that near point Q a 3.5-mA change in plate current is associated with a 40 volt total change in plate voltage:

$$r_p = \frac{e_b}{i_b} = \frac{40V}{3.5\ mA} = \frac{40}{.0035} = 11.4K$$

5. b -- para 52c(2)

This problem can be solved in two different ways.

(1) The sum of the voltage drops around the circuit must be equal E_{bb}:

$E_{bb} = e_b + I_bR_L$

Therefore: $I_bR_L = E_{bb} - e_b = 300 - 210 = 90$ volts.

(2) It is known that the steady value of plate current, I_b, is 7.0 mA. Thus the voltage drop across the resistor, I_bR_L can be calculated directly:

I_bR_L = (7.0 mA)(12,860 ohms) = 90 volts.

6. a -- para 51e(2)

7. d -- para 52c(1)

At the point where the load line intersects the plate voltage axis, the plate current is zero and there is no voltage drop across the load resistor, R_L . Therefore, the voltage drop across the tube must equal to the supply voltage, E_bb: 300 volts.

8. a -- para 50d(2)

$= r_p \times g_m$ = 9,000 ohms x 3,000 micromhos

= 9,000 ohms x .003 mhos

= 27

9. c -- para 52a, 52c(2), 56a

10. c -- para 52c, d; Attached Memorandum, fig. 3-5

In figure 3-5 a horizontal line drawn from point C (E_{CC} = -4V) to the plate current axis shows the plate current to be 4.6 mA.

11. d -- para 52c, d

When the signal voltage swings 4 volts positive, the grid voltage will be -2 volts ($E_{CC} + e_s = e_g$, or -6 + 4 -2) and the corresponding point of operation will be point B. When the signal voltage swings 4 volts negative, the grid voltage will be -10 volts and the point of operation will be point F.

12. b -- para 52d(2), 56d(1); fig. 65

13. b -- para 52c(1)

When the load line intersects the plate current axis, the voltage across the tube is zero ($e_b = 0$). Thus, at this point the current in the plate circuit is limited only by R_L and is found to be:

I_b E_{bb}/R_L = 250/50K = 5 mA.

14. a -- para 53g, 54b

15. c -- para 56a; fig. 65

16. a -- para 56c; fig. 65

When the signal voltage swings 3 volts negative, the grid voltage will be -7 volts (operating point G), and the plate current will be approximately 5 mA. When the signal voltage swings 3 volts positive, the grid voltage will be -1 volt (operating point A) and the plate current will be approximately 22 mA.

17. b -- para 56b(2); fig. 66

18. b -- para 57b; fig. 67

19. c -- para 57d

20. c -- Attached Memorandum, para 3-5

g_m = ac plate milliameter reading x 1,000

= 4.5 x 1,000 = 4,500 micromhos

Lesson 5..... Multielectrode Tubes

All references are to TM 11-662.

1. a -- para 60a

2. a -- para 61e(1)

3. d -- para 61b(2)

4. a -- para 61d(1)

5. a -- para 61d(2); fig. 70

6. d -- para 62f; fig. 71

7. c -- para 62e; fig. 71

8. b -- para 62i

9. a -- para 62j

10. a -- para 66d

11. d -- para 69

12. b -- para 70f

13. d -- para 68c(2); fig. 77

Changes in screen grid voltage, plate voltage, and grid bias all affect the transconductance, as shown in figure 77.

14. a -- para 70h

15. b -- para 71; fig. 86

16. c -- para 72f; fig. 87

17. c -- para 66d; fig. 75

18. d -- para 70g, h

The beam-forming plates are connected to the cathode and are used to eliminate the effects of secondary emission. They perform, therefore, the function of the suppressor grid.

19. c -- para 73d(2)

20. d -- para 74, fig. 92J

a. Symbol A represents a triple-diode-triode.

b. Symbol B represents a duo-pentode tube.

c. Symbol C represents a diode-triode-pentode tube.

d. Symbol D represents a triode-pentode tube.

PAGES 186 THRU 189

ARE EXTRACTS FROM TM 11-662

AND ARE PROVIDED AS A SEPARATE PDF DOCUMENT

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

EXTRACT

Paragraphs 1—12

United States Government Printing Office
Washington: 1952

CHAPTER 1

ELECTRON TUBES—THEIR DEVELOPMENT AND USE

1. Introduction

a. The success of modern military operations, as well as of the peacetime activities of the armed forces, depends in a great measure on signal communication facilities. Whether on the offense or the defense, in the front lines or far behind the lines, exchange of information is vital to the successful movement of personnel and equipment. On the ground, in the air, or below the surface of the seas, electronic devices are in daily use, and in every one of these uses the electron tube is a vital element (fig. 1).

b. Fundamentally, the electron tube is a valve which provides the means of conducting electrons through the enclosed space within a glass or metal container. As the electrons move from the end of one metallic conductor, or electrode, across the intervening space to the other electrode, or conductor, they are controlled more easily than if the same electrons were passing through a wire or any other type of conductor. This power to *control* electrons or electron currents and their associated voltages makes the electron tube the most useful single element in modern signal communication equipment. The present high level of signal communication and its tremendous versatility are due to the existence of the electron tube. Radio communication was utilized prior to the development of electron tubes, but it attained its present versatility only after the electron tube was invented.

2. Importance to Communication

a. In the armed forces, signal communication means many things and a wide variety of equipment. Radio communication is prominent among these, but it is just one method of exchanging *intelligence*, or information, between two points: namely, that method which depends on electromagnetic waves as the link. The intelligence that is transmitted in this fashion may be in code or it may be voice or music intended for specific points or for general reception over a wide area, or it may be both, plus other forms.

b. It is equally important to understand that the telephone, the teletype, and facsimile also are signal communication facilities, even if they use wire as the linking medium. These wired systems frequently are integrated into radio systems wherein the intelligence first spans a distance over wires and then is fed into a radio link for transmission to some remote point or, possibly, to a point not too distant which cannot be reached by conducting wire.

c. Radar, too, in its many forms, is a signal communication facility. It is conceivable that it might be placed in a special category, but even so it is embraced by the broad meaning of the communication art. Although public address systems and intercommunication systems are removed from radio systems, they are part of military signal communication facilities, as are many other equipments which transmit intelligence.

d. In all of these communication devices, the electron tube is the vital component and its unique feature is an extraordinary versatility. Here is a device which, at first view, appears to be rather fragile and capable of only limited types of service. But appearances are deceptive: The electron tube is unrivaled in sensitivity by any other electrical or mechanical device, since it can discriminate between quantities in terms of millionths of a second of time; yet it can handle electrical energy in terms of thousands of watts of power. Following are some of the types of service in which these tubes play an important part:

(1) *In social life.* The long-distance telephone, national and world-wide radio

broadcasting, sound motion pictures, public address systems, and television are all well known, and their impact on social customs and on national and international relations has been tremendous.

(2) *In commercial communication.* Air, land, and sea communication are carried on by means of radiotelegraphy and radiotelephony. Navigation aids, both aircraft and marine, have lessened the hazards of travel.

(3) *In industry. Electric-eye* control devices for automatically controlling quality, color, and size of manufactured products, and for performing all kinds of counting, sorting, timing, recording, and similar operations, have been invaluable to industry. Induction heating applications for production soldering, welding, and heat treatment of metals in metal fabrications have been instrumental in reducing factory time and costs.

(4) *In medical therapy.* X-ray therapy, diathermy for inducing curative artificial fevers, and high-frequency applications in *bloodless surgery* have provided vital tools for the medical profession.

(5) *In scientific research.* Atomic experimentation, electron microscopy, instrumentation, computer and recording devices have become practical realities.

(6) *In military communications.* Radar, fire-control apparatus, communication facilities between fixed and mobile units have increased the mobility and the power of land, sea, and air forces.

e. Finally, so numerous and varied are the applications of electron tubes that a new branch of engineering has been created, that of *electronics*, which encompasses the widespread applications of electron tubes.

3. Early Experimenters

a. The development of the electron tube and its associated communication circuits as they exist today was not the work of any one scientist. Rather it was the cumulative result of the researches, discoveries, and inventions of numerous investigators. Actually, to trace the very beginnings of certain important discoveries, which later led to fruitful results, would necessitate a discussion beyond the scope of this manual. However, for all practical purposes, modern radio art may be said to have had its beginnings toward the end of the last century when, in 1883, Thomas A. Edison was experimenting with his newly invented incandescent lamp.

b. The Edison incandescent lamp may be regarded, in a sense, as the forerunner or prototype of the modern electron tube. Edison noticed that the carbon wire filament of these first incandescent lamps burned out at the point at which the filament entered the glass bulb. Looking for an explanation, he inserted a second conductor or *plate* into the lamp (this is basically the structure of the *diode*, or two-electrode tube of today), and recorded in his notebook that this *dead end* wire or *plate*, when connected through a current meter to the positive side of the battery, showed a flow of current (fig. 2) across the space between the filament and the *plate*. Normally, such an arrangement constituted an open circuit; therefore, current flow, according to the knowledge of electrical circuits at that time, was regarded as an impossibility, for here was an *open circuit*. Edison could find no satisfactory explanation for this phenomenon, which became known as the *Edison effect*.

c. An accurate and epoch-making explanation of the *Edison effect* was advanced in 1899 by a British scientist, Sir J. J. Thomson. He presented the theory that small, negative particles of electricity, called *electrons*, were emitted by the filament in Edison's lamp as a result of operating it at incandescence or white heat. He said, further, that these electrons, because of their negative charge, were attracted to the positively charged plate. Thus, as long as the filament was heated to the proper temperature, electrons would flow from it to the plate. This movement of electrons constituted a flow of electron current, and the electron stream was the means by which the gap was bridged across the intervening space between the filament and the plate, thus closing the circuit.

d. Thomson's findings came to be known as the *electron theory*. Briefly, this theory views

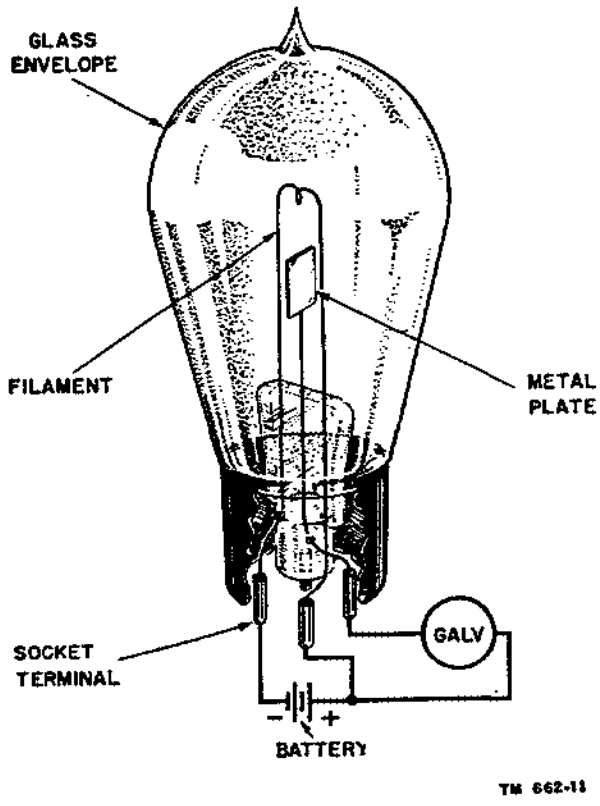


Figure 2. Circuit of Edison's two-electrode tube.

the atoms of all matter as being composed of infinitesimally small, individual negative particles, or electrons, held within the atom by the attraction of a central nucleus of positively charged particles called *protons*. Under suitable conditions, as by the application of heat to a substance, some of the electrons within the substance could be liberated. This extremely important theory gave great impetus to subsequent research, and led to great developments in electron tubes.

e. Equipped with this knowledge, other scientists explored further. The next significant development of far-reaching importance was the work of J. A. Fleming, an English scientist, who designed the first practical electron tube. Fleming observed from Edison's work that, when the plate connection was made to the negative rather than to the positive side of the battery, the current was zero (fig. 3). This property provided the basis for the operation of the electron tube as a *rectifier*, that is, as a device for the conversion of alternating current into direct current. Fleming, calling his modified version of Edison's two-electrode lamp a *valve* (the term still used for the electron tube in England), thereby provided a superior *detector* to supplant the comparatively insensitive crystal detectors then being used in radio receivers in Guglielmo Marconi's system of wireless telegraphy. The crystal detector was a parallel development, which, following the experiments of numerous predecessors, Marconi made a reality in 1901 when his historical signals of the letter *S* (three dots) spanned the Atlantic Ocean. With the advent of Fleming's valve, the two major lines of discovery and invention, from which the radio art evolved, were joined.

f. Fleming's valve was a two-electrode tube. For several years it was the only electron device in use. At this point it seemed that the progress of wireless communication had reached its practical limit, a limit determined by the existing methods and devices used for transmitting and receiving radio signals. The most powerful

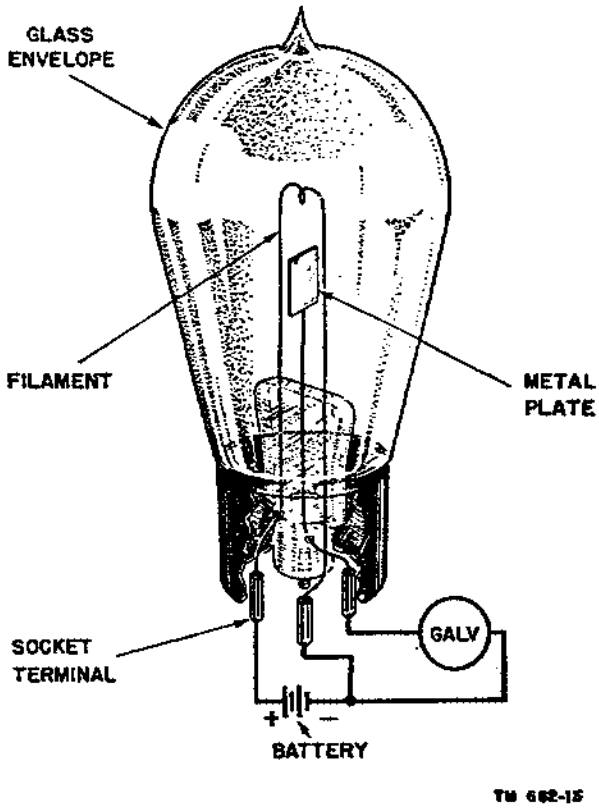


Figure 3. With plate connected to negative side of battery, current through tube is zero.

transmitters could transmit signals to receiving sets more than several hundred miles away, but the reception of such signals was undependable. The range and the dependability of radio communication could be increased only by the development of some method by which the weak signal could be amplified. The vacuum tube developed by Lee DeForest in 1907 supplied this needed means of amplification. Later improvements of this tube have made possible the reception of radio signals millions of times too weak to be audible without amplification.

g. DeForest, by inserting an extra electrode in the form of a few turns of fine wire between the filament and the plate of Fleming's valve, made the tube an *amplifier.* DeForest called the third electrode the *control grid.* It provided the desired amplification by virtue of the fact that relatively large plate current and voltage changes could be controlled by small variations of control-grid voltage without expenditure of appreciable power in the control circuit. DeForest called his three-electrode tube an *audion,* a designation superseded in present-day usage by the term *triode* (fig. 4).

4. Tube Types

a. Each kind of electron tube is capable, generally, of performing many different functions, and therefore initial classification of these tubes is not based on function but upon their physical construction (fig. 5). The envelopes or housings are made of glass or metal or, in a few isolated cases, of both materials. The absence or presence of air or other gases in the envelope distinguishes the two fundamental classes of electron tubes. In the *vacuum* tube, all gases have been removed; in the *gaseous* tube, after all air has been removed, a small amount of mercury vapor or inert gas is placed within the envelope.

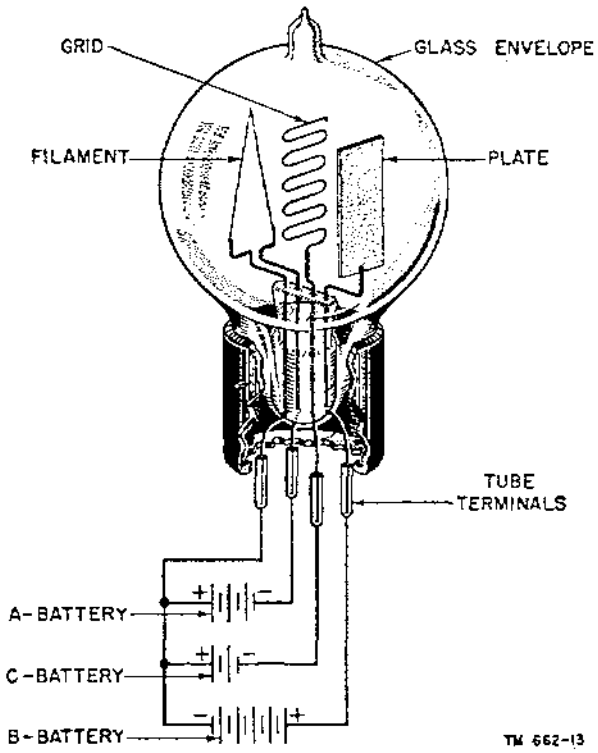


Figure 4. Construction of DeForest's three-element tube, or triode.

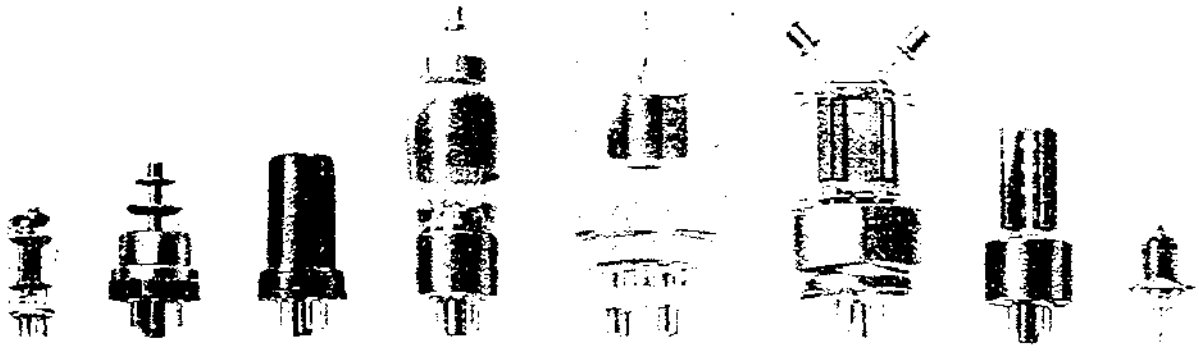


Figure 5. Representative electron tubes.

b. In all electron tubes, one electrode, called the *cathode*, is the emitter of electrons, and it must be heated to cherry red or to incandescence before the electrons are freed from its surface to move across to the second electrode, or *anode*. In vacuum tubes, sometimes called high-vacuum or hard-vacuum tubes, the cathode is in almost every case (the photoelectric tube is excepted) heated by some external source of power, and these tubes, therefore, are not distinguished as to type of cathode. In gaseous tubes, sometimes called soft tubes, a further subclassification is made into *hot-cathode* and *cold-cathode* types. In the first type, the cathode is heated to the proper temperature for emission by some external source of power; in the second type, the gas within the tube is ionized, then the cathode is bombarded by positive ions which raise the cathode to the correct emission temperature.

c. Both vacuum tubes and gaseous tubes of either the hot- or cold-cathode type are further classified as to the number of active elements or electrodes contained inside the envelope. The simplest of these, described above, contains two elements and is known as a *diode*. A tube which contains three elements is known as a *triode*, and a tube with four elements is called a *tetrode*. If it contains five elements it is a *pentode*. In each instance, the type classification indicates the number of elements which make up the tube. In the following chapters each of these tubes is illustrated and the differences between them fully explained.

5. Tube Functions

The functions performed by electron tubes are many and varied, but for convenience these functions may be consolidated into a few general groups. Each function is determined not only by the tube type but also by the circuit and its associated apparatus.

a. A general capability of the electron tube is to alter an ac (alternating current) so that it becomes a pulsating dc (direct current) (fig. 6). Associated apparatus can smooth out the variations in the current and the system as a whole can be said to change an alternating current into a constant-amplitude direct current. This function provides convenient sources of d-c voltage when the only available primary source of electrical energy is an a-c power line or an a-c generator. These d-c voltages may be as low as a fraction of a volt and as high as tens of thousands of volts. The action of changing an alternating current into a pulsating direct current is referred to in general terms as *rectification*, and the electron tube which does this is called a *rectifier*.

b. Another significant and useful capability of the electron tube, and perhaps its most important function, is described as *amplification* (fig. 7). A stronger signal voltage may be obtained from the tube than is fed into it. In effect, the tube is a signal voltage magnifier. A signal equal to 1 volt fed into the input system of the amplifying tube may appear as 20 volts at its output. Different arrangements provide for different amounts of signal amplification.

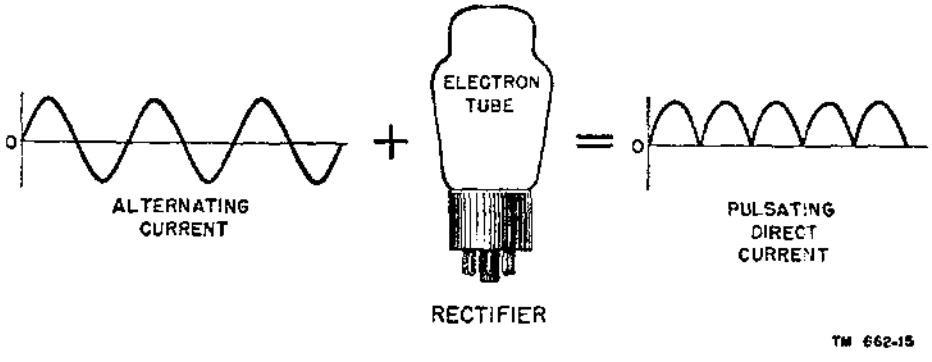


Figure 6. Function of tube as rectifier of alternating current.

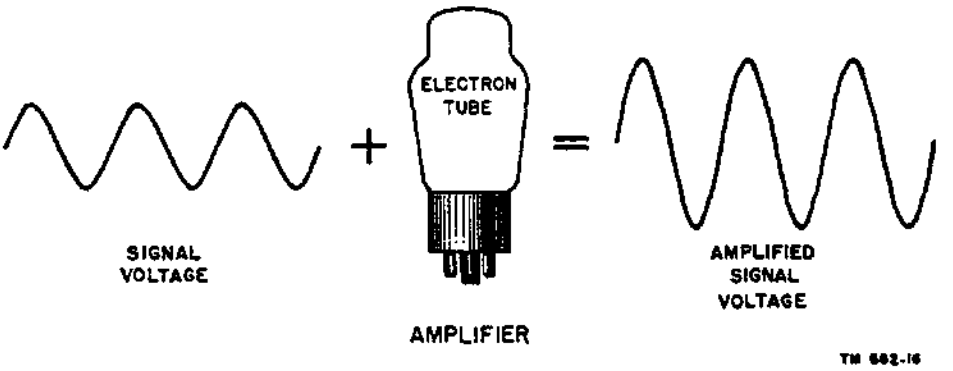


Figure 7. Function of tube as amplifier.

(1) This amplification ability of the electron tube accounts for the advanced development of modern-day communication. It is the basis of all long-distance telephony, because repeaters (electron-tube amplifiers) compensate for the energy losses encountered in the wires. Also, by means of public address systems, the electron tube is used to amplify the voice of an individual so that thousands of people gathered together may hear it clearly.

(2) Amplification by electron tubes makes radar possible because it strengthens the echo signal received from the target so that it can be made visible on a special screen. It is responsible for teletype operation. Television would be impossible without it. Amplification is essential in radio transmitters and receivers of all kinds to build up electrical energy to proportions necessary for proper operation of the various circuits of the equipment.

c. Still another extremely important facility offered by the vacuum tube is the conversion of electrical energy existing as direct current and voltage into alternating current and voltage (fig. 8). Used in this manner, the tube draws energy from a d-c source and, in conjunction with suitable apparatus, *generates* high-frequency oscillations. This function has been responsible for innumerable developments in the communication field.

(1) The principle of oscillation underlies the operation of virtually every type of radio transmitter, large or small, fixed or portable. As a generator of high-frequency oscillation, the electron tube replaces ponderous rotating machinery. Even more important is that specialized oscillators opened up the very-high- and ultra-high-frequency and microwave regions for operation. These extend from approximately 30 mc (megacycles) to tens of thousands of megacycles. The use of these frequencies has helped to overcome the

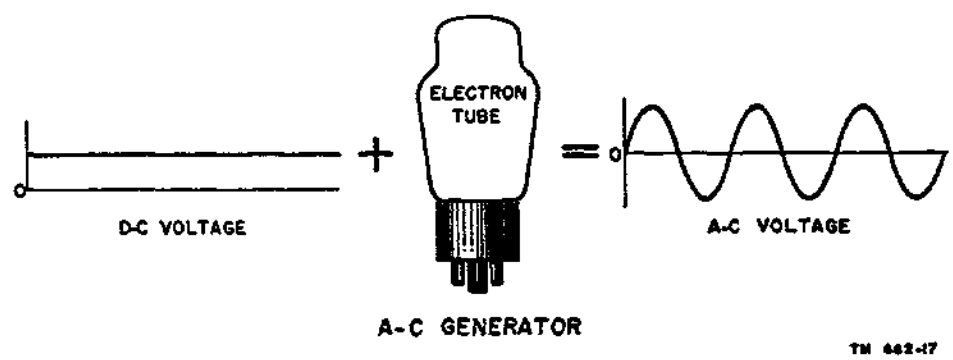


Figure 8. Function of electron tube as generator of alternating current.

communication limitations caused by changing seasons and the effects of weather. It helped create new techniques, among which are radar, television, and radio facsimile.

(2) Availability of these high-frequencies has made possible the convenient use of low power and the design of small receivers, transmitters, and antennas. All of these are important contributions and make feasible radio contact between planes and tanks, or landing forces and ships.

d. The electron tube can modify the shape of electric current and voltage waveforms; that is, it can change the amplitude of these quantities relative to time. Voltage and current shaping (figs. 9 and 10) are vital to the operation of numerous electronic devices. It is used in code transmission, the timing of circuit actions in radar, in the production of television pictures, and in the operation of teletype equipment. Electronic computers could not operate without waveshaping of the currents and voltages present in the equipment.

e. A singular type of electron tube is capable of converting light energy into electrical energy. This is the *photoelectric tube,* also called the *phototube.* In contrast to the conventional electron tube, the phototube does not employ an incandescent electron source. Instead, electrons are liberated from a specially prepared surface inside the tube when radiant energy strikes the material. The stream of charges thus developed is an electric current and gives rise to a voltage in the system. The net result is a voltage output for visible or invisible light input. Although not as versatile as the conventional electron tube, the phototube has many uses. It affords a means of using light energy to control devices or systems or to operate many kinds of equipment. The reproduction of sound from a photographic image on a film is one of many applications of the phototube.

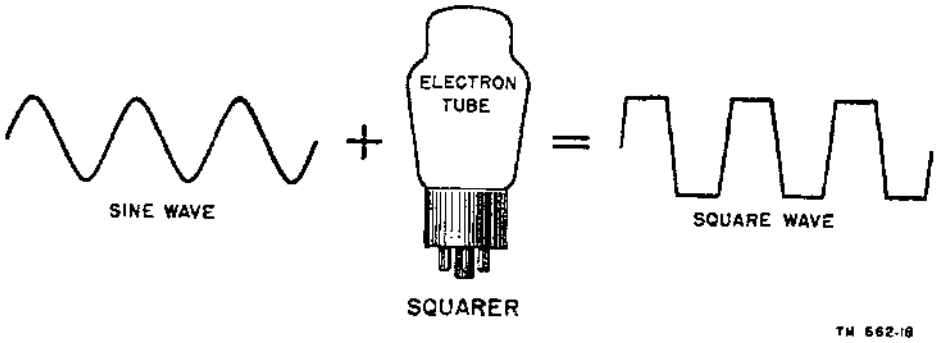


Figure 9. One type of waveshaping accomplished by electron tubes. The input signal is a sine wave; the output is a square wave.

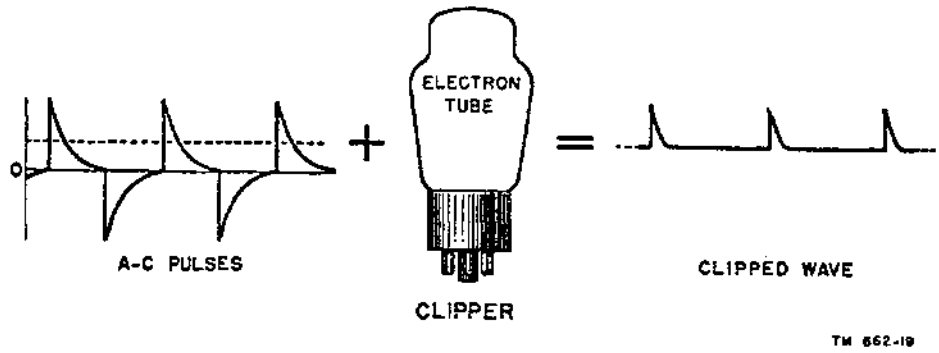


Figure 10. Another type of waveshaping. Only parts of the positive peaks of the input signal are present in the output.

6. Summary

a. The term *electron tube* is a general one under which are grouped vacuum tubes, photoelectric cells, phototubes, cathode-ray tubes, and many other types. The operation of all electron tubes is based on the controlled flow of electrons within the tube structure.

b. In their various forms, electron tubes are found in devices that perform some necessary function in almost every phase of social, industrial, scientific, and military life.

c. Probably the very first important step in radio development was the discovery of the *Edison effect.* Many other scientists contributed important discoveries and inventions. Thomas, Fleming, DeForest, and Marconi are among these early pioneers.

d. DeForest's original three-electrode tube was called an *audion,* a designation now superseded by the term *triode,* and Fleming's original diode was termed a *valve,* the designation that still is used in England instead of the term *tube.*

e. According to the number of elements they contain, electron tubes are classified as diodes, triodes, tetrodes, or pentodes.

f. Among the many special functions which they are capable of performing, that of amplification of electrical energy is perhaps the outstanding feature of electron tubes. The diode, however, does not provide amplification, but it performs another basically important function—rectification.

7. Review Questions

a. What are the two classifications of electron tubes as distinguished by the presence or absence of gas within them?

b. List and describe briefly 12 or more general uses for electron tubes.

c. What are some of the various services included under the general term *communication?*

d. Name some types of signal communication facilities used by the armed forces.

e. Explain the Edison effect.

f. Explain briefly the contributions to the radio art by Fleming, Thomson, Marconi, and DeForest.

g. What are the names for two-, three-, four- and five-element tubes?

h. What is the linking medium in radio broadcasting, facsimile, teletype, telephone, radar?

i. Name and describe briefly some of the special functions which electron tubes can perform.

j. In what sense is an electron tube an amplifier?

k. How does a phototube differ from an ordinary electron tube?

l. What special capabilities of electron tubes differentiate them from electrical and mechanical devices designed for similar types of service?

CHAPTER 2

ELECTRON EMISSION

8. Basic Theory of Electron Emission

a. The operation of all electron tubes depends on an available supply of electrons. Electron emission can be accomplished by four methods, the most important of which is *thermionic emission.* Thermionic emission is the liberation of electrons from a metallic emitter by the application of sufficient heat. Other methods are secondary emission, photoelectric emission, and cold-cathode emission. All of these are discussed later in this chapter.

b. In the *vacuum* type of electron tube, as much air as possible is withdrawn from the envelope and all the electrons needed for operation of the device are obtained from the emitter. In the other general category of electron tubes, known as the *gaseous* type, all air is removed from the tube and a small amount of mercury or some inert gas (neon, argon, xenon, etc.) is placed within the envelope. The emitter furnishes the primary supply of electrons. The emitter output provides electron bullets for ionization of the gas atoms. This process is explained in a later chapter of this manual.

c. The *atomic theory,* which maintained that the atom was the fundamental *building block of matter,* gave way to the *electron theory,* which revealed that the electrons and protons which comprised the atoms were actually the *primary* particles of matter. Accordingly, all electron-tube and electrical phenomena now are explained in terms of the electron theory.

d. The electron theory states that all matter consists of two basic electrical charges: *positively charged protons* and *negatively charged* electrons. These charged particles are the principal and fundamental building blocks which form the atoms comprising the 90-odd elements constituting all matter. Recent investigations have disclosed neutrons, positrons, mesotrons, and photons, but their study concerns the chemist and the nuclear physicist. The early electron concept, as suggested by Nels Bohr, is satisfactory to students concerned with electronics and provides a useful physical picture necessary for the study of the properties of electricity.

e. In any material, confined in a given volume, the atoms or molecules are in a state of random motion around a mean position. The extent of this motion is determined by the nature of the substance and its temperature. In solids, this random motion is restrained the greatest amount. In liquids, the restraint is less, and in gases, it is the least, almost none. This explains why a solid substance holds its shape unless forces are applied to change it, why a liquid changes its shape to suit its container, and why a gas attempts to fill the space in which it is liberated.

f. Inasmuch as the item of concern is the emission of electrons from metals which may or may not bear coatings of certain chemical elements, it will be well to discuss the action of atoms and molecules. It is significant to note that the amount of random motion in atoms and molecules is a function of temperature. If the temperature of a metal is reduced, its amount of random motion is reduced, and its resistance to the flow of electric current is reduced. This action can be explained by saying that the electrons which comprise the current meet less opposition and experience fewer collisions with the atoms, because the atoms are restricted in their movements.

g. On the other hand, if the material is heated, energy is added to the energy already possessed by the atoms and the molecules in motion, and they perform greater movements at greater velocity. When a fuse blows, the action is simple. The high current overload

heats the fuse material so that the kinetic energy of the atoms and molecules is sufficient to disrupt the molecular organization of the metal completely, and it passes instantly through the stage of liquefaction and turns into vapor. Consequently, it becomes a part of the surrounding air.

h. In like fashion, the free electrons in a substance held at normal temperature perform random motion in their travel between atoms, as illustrated in exaggerated form in figure 11. This takes place at a relatively high velocity. Since these electrons move around so rapidly, one is tempted to ask the natural questions: Why don't they move out of the material—for instance, a piece of wire? Why don't they break through the surface and get into free space? Some do just that, but they are so few in number as to be of no importance. The generally accepted description of what happens is that there is no liberation of electrons until special conditions are created deliberately. The reason for such behavior was first explained by O. W. Richardson in 1901. Richardson's theory concerning conditions at the surface of a hot metal has subsequently been accepted by scientists.

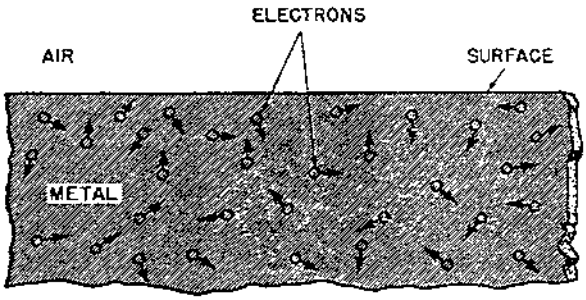


Figure 11. Free electrons having random motion at normal temperature within a metal.

i. Richardson advanced the idea that the boundary of a substance exerts a force in a direction toward the inside of the substance, and so prevents the electrons from leaving the material by penetrating through its surface. For an electron to break through the surface, it is necessary that its velocity, as it approaches the surface, be greater than a critical amount, in order that kinetic energy be sufficient to overcome the barrier at the surface which tends to keep it within (fig. 12). This behavior of different materials is described as the *work function* of the substance. As a matter of convenience, this constant usually is expressed in *electron volts of energy* or simply *electron volts.* Consequently, if an electron advances from a point of zero potential to a point that is 10 volts positive, it has acquired 10 electron volts of energy. Under such conditions, the velocity of the electron is described as 10 electron volts or, for convenience, 10 volts. *Potential barrier* is another name for the action that occurs at the surface of a material and is also expressed in electron volts.

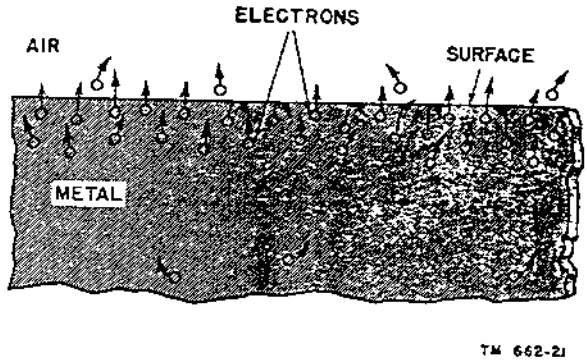


Figure 12. Free electrons escaping into air and to surface of metal.

j. Various substances have certain work functions. A substance like thoriated tungsten, which is commonly used in electron tubes as the source of electrons, has a work function rating of 2.63 volts. On the other hand, nickel coated with barium oxide has a work function rating of about 1 volt. The lower this rating is the more easily an electron can penetrate the surface and leave the material. Consequently, oxide-coated substances often are used as emitters of electrons in electron tubes when a large electron flow is desired. In terms of electron velocity, the lower the work function rating, the less the velocity of the electron needs to be in order to leave the surface. This gives rise to the use of different kinds of electron-emitting substances in electron tubes.

k. The statements made so far show that the emission of electrons by a substance is possible

by giving the electrons such velocity that they will overcome the restraining forces present at the surface. This means adding energy to the amount already possessed by the electrons. Several methods of doing this will be described presently.

9. Thermionic Emission

a. Thermionic emission is one means of securing an adequate supply of electrons for the operation of both vacuum and gaseous kinds of electron tubes. By definition, *thermionic emission* is the emission of charged particles from a heated cathode or emitter. The acceleration of the electron to the velocity required for it to leave an emitter is accomplished by means of heat applied by any one of a number of processes. Consequently, the name *thermionic tubes* sometimes is used to describe electron tubes.

b. In thermionic emission, heat is the form of energy that is used to liberate electrons from the substance. When heat is applied to a metal and the temperature is raised sufficiently, some of the heat energy is transferred to the electrons. The electrons then move with greater velocities than previously. If the temperature is high, so that the motion of the electrons reaches sufficient velocity, they will escape through the potential barrier of the emitter into space. When this action is controlled, as in the case of electron tubes, it can be made to provide a continuous stream of electrons.

c. For a given type of emitter, there is a definite rate of thermionic emission at each temperature. The rate depends on the type of emitter material used and the temperature of the emitter. This process is fully described in chapter 3.

10. Other Types of Electron Emission

a. Thermionic emission sometimes is referred to as *primary emission* to distinguish it from another type of electron emission called *secondary emission.* In this comparison, primary emission signifies that emission takes place directly from an emitter substance by the application of heat, or other means; in secondary emission, electrons are detached from a body as the result of its being *bombarded* by electrons emitted from a primary source (fig. 13). When, for example, a stream of high-velocity electrons strikes a metallic substance, these bombarding electrons impart sufficient energy to the electrons within the metal to enable them to break through the potential barrier. Although in the figure only one secondary electron is shown to be released for each primary electron, in actual practice the number of secondary electrons may be more, depending on the material from which the body is constructed. In some vacuum tubes, secondary emission takes place in the normal tube operation, but usually it is undesired and provision is made to prevent it. However, this condition is created purposely in other tubes to obtain special operating characteristics.

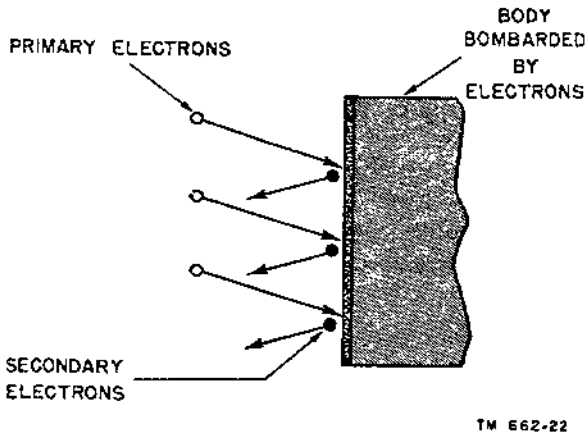


Figure 13. Secondary emission caused by electron bombardment.

b. Another method of producing electron emission is by the application of light. Light, an electromagnetic radiation, is a form of energy. The theory by which electrons are liberated from substances when electromagnetic waves of the proper frequency impinge on them is very complex and is beyond the scope of this book, but it is an accepted fact that electron emission does take place. Consequently, when energy in the form of light strikes a *photosensitive* metal, electrons are liberated from this metal under impact of the energy of the light rays (fig. 14). This is known as *photoelectric emission.* The photoelectric current is directly proportional to the intensity of illumination. All photoelectric tubes, or photo-

tubes used in countless applications for control and detection depend on photoelectric emission for their operation.

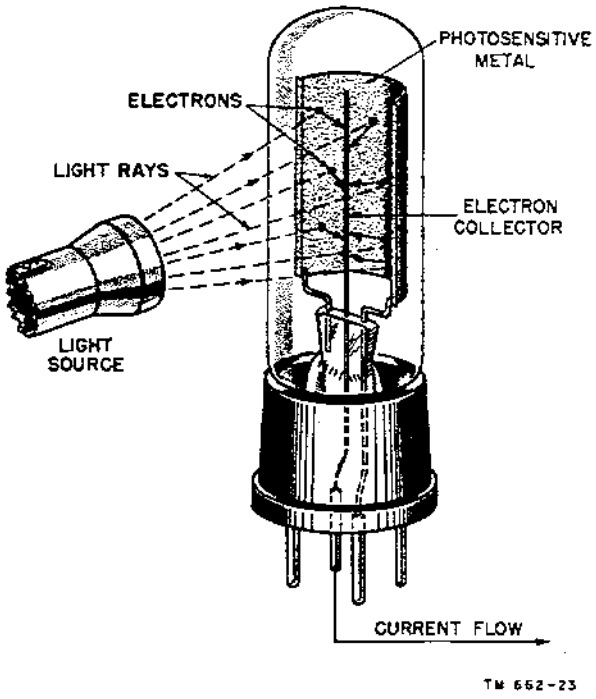


Figure 14. Photoelectric emission of electrons.

c. Still another method is called *cold-cathode emission.* In this type of emission, electrons are virtually pulled out of a substance by the power of an extremely strong electric attracting force. Since high voltages which raise many problems are required in this method, cold-cathode emission is not commonly used.

11. Types of Emitters

Electron emitters are classified according to the method used to heat them. In the *direct method,* the emitter is called a *filament* or *directly* heated cathode, and the electric current is applied directly to the cathode. In the *indirect method,* the emitter is called an *indirectly* heated cathode and the electric current is sent through a separate *heater element* which is located inside the emitting cathode and transfers its heat energy to it by conduction. Both methods can use either alternating current or direct current.

a. DIRECTLY HEATED ELECTRON EMITTERS (fig. 15). A directly heated electron emitter or *filament* is usually of the general construction shown in A. The radio symbol for the filament in a vacuum tube is shown in B. Physically, the filament usually is shaped either in the form of an inverted V or an inverted W. The filament voltage required to produce electron emission is applied across the filament prong terminals located in the base of the tube. When current flows through the filament circuit, the filament emits electrons when it reaches emission temperature. Filament materials are tungsten, thoriated tungsten, or metals that have been coated with alkaline-earth oxides. In the latter case, the electron-emitting material is the coating; the metal core is used to carry the heating current. Some directly heated oxide-coated filaments require comparatively little heating power, and for this reason they are extensively used in tubes designed for operation from batteries and in portable equipments. An added advantage of the directly heated electron source is the rapidity with which it reaches electron-emitting temperature. Since this is almost instantaneous, many equipments that must be turned on at infrequent intervals but must be instantly usable use directly heated tubes. Usually these are of the oxide-coated variety.

b. INDIRECTLY HEATED ELECTRON EMITTERS (fig. 16). For the indirectly heated type of electron emitter, shown in A, the cathode electrode is the emitting element. B represents the radio symbol as it appears in vacuum tubes.

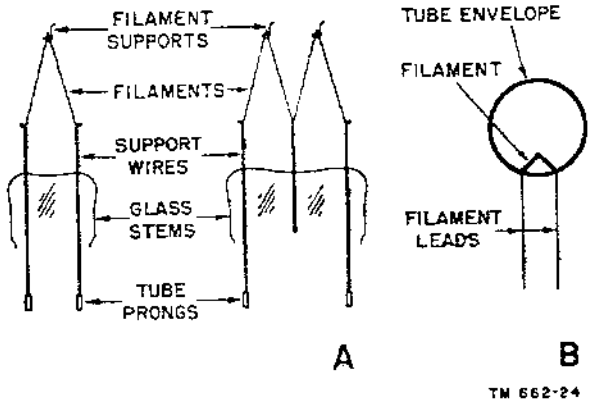


Figure 15. Directly heated filaments and schematic symbol.

The electron source is an oxide coating on the cathode electrode. It is heated to emission temperature by the heat from the heater. The electric current flows through the heater, located within the cathode that surrounds it. Heat energy produced in the heater by the electric current is conveyed by conduction to the cathode. The majority of electron tubes are of the indirectly heated type, because of the practicability of operating the tube from alternating-current supply lines. Variations in heater current do not cause a fluctuating output in electron emission (for all practical purposes) because the temperature of the cathode remains fairly constant when the a-c input reverses its direction. The constant temperature is caused by the inability of the cathode to cool off quickly when the alternations are approximately 60 cps. This is not true for directly heated emitters, and, consequently, special circuits are necessary to adapt these tubes to an a-c filament supply.

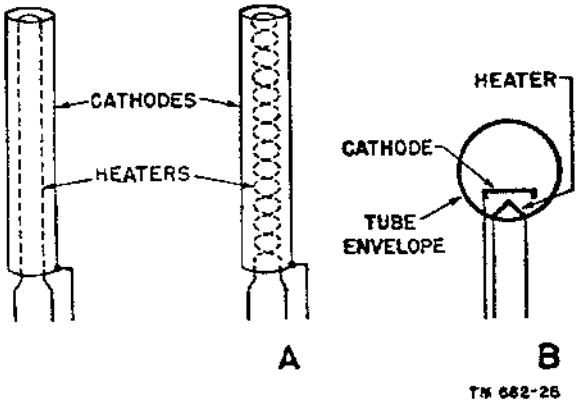


Figure 16. Indirectly heated emitter and schematic symbol.

c. FACTORS DETERMINING EMISSION. The amount of electron emission that can be obtained from an incandescent filament or a cathode depends on various factors. Essentially, it is determined by the temperature of the emitter, which in ordinary vacuum-tube operation is determined directly by the amount of current applied to the filament. In general, the higher the temperature of the emitter, the higher is the resultant emission. However, a practical limit must be considered. The substances used in the manufacture of emitters are designed for operation within definite temperature limits to assure maximum operating life and efficiency. *Excessive* temperature causes extremely rapid deterioration of the emitter, which reduces its useful life. This applies equally to all types of tubes using heated electron emitters.

12. Materials Used

a. Very high temperatures are required to produce satisfactory thermionic emission. As previously mentioned, the materials best suited for the purpose are tungsten, thoriated tungsten, and oxide-coated core materials. Platinum and nickel are examples of oxide-coated core materials. Of all these substances, tungsten possesses the greatest durability, and therefore, is used in tubes which may be subjected to heavy overloads. Similar service is also performed by thoriated-tungsten filaments. Both of these generally are found in equipments such as transmitters, since they can withstand high voltages and rigorous conditions.

b. Thoriated-tungsten filaments are manufactured by mixing thorium with tungsten. The thorium coating behaves as a profuse emitter of electrons and gradually evaporates during use. As it boils off, it is replenished from inside the tungsten filament wire. At the same time, a gradual evaporation of the wire occurs; consequently, it becomes thinner with time. Eventually one part of the filament becomes too weak to carry the current and it burns out.

c. Thoriated-tungsten filaments usually are operated at temperatures of about 1,900° C. At this point, the filament becomes bright yellow. Tungsten, on the other hand, is operated at approximately 2,200° to 2,500° C. and glows with a white light. The evaporation of tungsten is like that of thoriated tungsten; consequently, longest tube life is attained by keeping the voltage constant across the filament and allowing the current to adjust itself in accordance with the changes in filament resistance as the wire becomes thinner and thinner.

d. The most efficient electron emitters are the oxide-coated filaments and cathodes. These coatings usually are barium or strontium oxides. The electron emission takes place from the oxide coating; the core carries the heating

current. The operating temperature is approximately 800° to 1,150° C.

13. Summary

a. According to the electron theory, all matter is composed of two fundamental electrical charges—namely, protons and electrons. Different combinations of both form atoms. A molecule consists of one or more atoms, depending on the particular element.

b. Free electrons in a substance at normal temperature perform random motion in their travels between atoms.

c. Some types of electron emission are *thermionic, secondary, photoelectric,* and *cold-cathode.*

d. Electron emitters are either directly or indirectly heated by an electric current. Because alternating current is the principal source of electrical power available, the indirect means of heating electron emitters is most widely used.

e. Oxide-coated materials for cathodes are used most commonly because of their high emission rate. Where higher voltages are involved, mechanical strength is a requirement, and therefore, tungsten or thoriated tungsten is used.

14. Review Questions

a. What are the building blocks of matter?

b. Name the two fundamental particles found in the atom.

c. State three methods by which electrons can be liberated from a material.

d. What enables electrons to leave a material?

e. What is meant by the terms *work function* and *potential barrier?*

f. Name three materials which are used as electron emitters in electron tubes.

g. Which type of substance emits electrons most profusely?

What is meant by indirect heating of an emitter? By direct heating of an emitter?

h. What is the name generally applied to an indirectly heated emitter? To a directly heated emitter?

i. What is the effect of operating emitters at excessive temperatures?

j. Why are tungsten and thoriated-tungsten emitters operated at constant voltage instead of constant current?

k. What is the difference between primary emission and secondary emission?

l. Relative to the source voltage, what advantage does indirect heating offer over direct heating of emitters?

m. Which operates more rapidly, the indirectly heated emitter or the directly heated emitter?

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

EXTRACT

Paragraphs 15—29

United States Government Printing Office
Washington: 1952

CHAPTER 3

DIODES

15. Construction

a. The simplest type of electron tube is the *diode.* It consists of two elements or electrodes, one of which is an *emitter of electrons* and the other a *collector of electrons.* Both elements are enclosed in an envelope of glass or metal. Although this discussion revolves around the vacuum diode from which most of the air has been removed, it should be understood that gaseous diodes also exist. The term *diode* refers to the number of elements within the tube envelope rather than to any specific application. In this connection, the complete *electron-emitting system* is treated as one element. Different names are applied to the diode to indicate the specific function of the tube in any particular electrical circuit. As one example, the diode can change alternating current into direct current; it is then a *rectifier,* and the tube is named accordingly. Therefore, when discussing the basic diode, reference is made to the tube as a type, rather than to any of its applications.

b. The electron collector is called the *plate* and the electron emitter is called the *cathode.* Although the latter term more specifically applies to the indirectly heated type of emitter, whereas the directly heated type of emitter is referred to as the *filament,* the term *cathode* usually is used regardless of the method of heating. This usage is not so odd as it may seem, since the majority of tubes in use today are of the indirectly heated type.

c. In directly heated tubes, the filament is of the general construction illustrated in figure 15, showing two typical filamentary cathodes. The type shown at the left is known as an *inverted V,* and that on the right as an *inverted W.* The filament is held in place within the tube envelope (glass or metal) by means of suitable metal supports firmly resting in the glass stem of the tube. It is suspended from the top of the tube by a metal support which allows for the expansion of the filament wire when heated. The filament voltage is applied across the prong terminals of the filament in the tube base. Figure 17 is a cross-sectional view of a simple diode tube, showing the internal construction, tube base, and wiring.

d. In indirectly heated tubes, the cathode-heater design can be either of the two common types shown in figure 16. The heater wire is usually either U-shaped, as shown on the left,

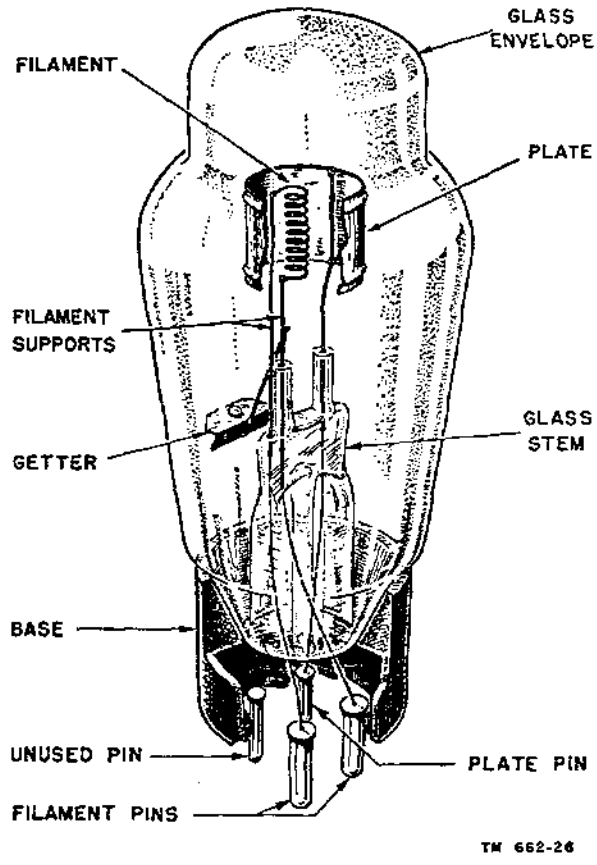


Figure 17. Cross-sectional view of simple half-wave diode of filament type.

in A, or it can be twisted throughout its length, as on the right, in A. In indirectly heated tubes, the cathode is an oxide-coated cylindrical sleeve, usually of nickel, which encloses the heater wire. The heater is insulated from the nickel sleeve by an Alundum coating on the heater wire or by passing the heater wire through fine parallel holes in an Alundum tube. In directly heated high-power tubes, the cathode heater is constructed of tungsten and thoriated tungsten, since high voltages tend to destroy oxide-coated cathodes.

e. The plate is usually of cylindrical construction, although frequently it has an elliptical form. In modern tubes it surrounds its associated emitter, as in figure 18. The metals used for the diode plate (and the plates of most other tubes) usually are nickel, molybdenum, monel, or iron. A tube which contains one emitter and a single related plate is identified generally as a *half-wave rectifier*, for reasons which will be explained later. Another name for tubes of this kind is simply *diode*.

f. Another structural organization of diode tubes utilizes two diode sections inside a single envelope, each section consisting of an emitter with its own heater and its related plate (A of fig. 18). A tube that contains a pair of diode sections is called a *duo-diode*, or a *full-wave rectifier*. The choice of term depends on the application of the tube. Rectifiers usually are associated with circuits which change alternating current to pulsating direct current at reasonably *high* levels of electrical power, whereas the name diode or duo-diode is applied to tubes which perform the same function in connection with radio signals. These represent appreciably lower levels of electrical power. The differences will become much clearer later.

g. The circuit symbol for an electron tube with two cathodes and two plates is shown in the lower part of A. The two heaters, one for each cathode, are shown joined in series. The same heater current flows through both. The two extreme terminals are arbitrarily labeled H1 and H2. In some tube types, a center tap is provided in the heater circuit. This is shown by the dotted line labeled H3. The two cathodes, K1 and K2, are independent of each other. The plates associated with these cathodes are des-

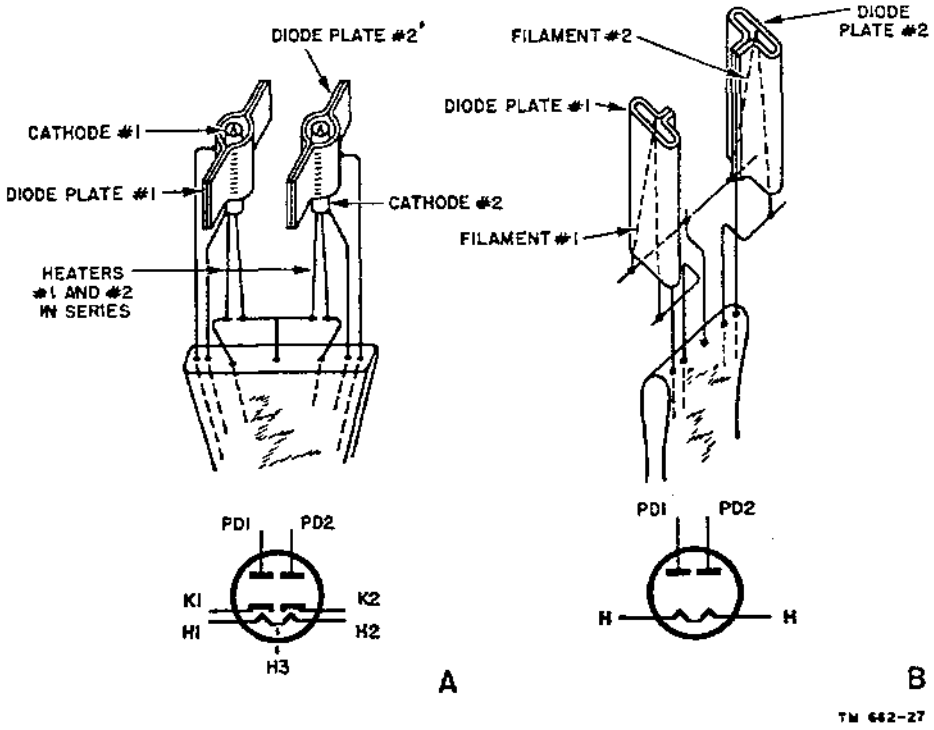


Figure 18. Construction of duo-diode and its schematic representation.

ignated appropriately PD1 and PD2, corresponding to the markings for the cathodes. The circle around all of the electrodes symbolizes the tube envelope.

h. B shows a different physical arrangement of two diodes within a single envelope. This is a directly heated tube in which oval-shaped plates surround the inverted V-shaped filament emitters. These filaments are connected in series, as shown in the related circuit symbol. Again, the two plates are independent of each other and each bears its own identifying designation.

i. Modifications of tube structure occur among the many diode tube types. Two of these are illustrated in figure 19. One heater can serve a single cathode, which has sufficient emission to serve two independent plates, as in A, or two series-connected heaters can serve two cathodes joined to each other internally and terminated at a single tube base pin, as in B. The plates are separate from each other for connection to individual circuits.

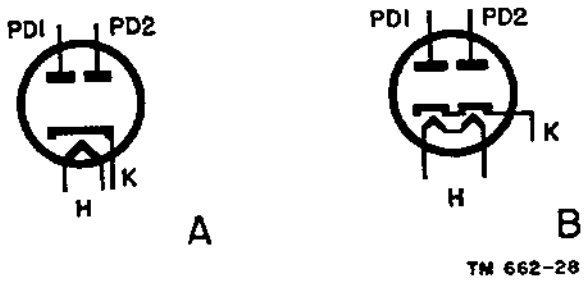


Figure 19. Other schematic representations of duo-diodes.

j. One of the essential requirements of a *vacuum* tube is that it must remain practically free of internal gases during operation. Every precaution is taken during manufacture to pump all the air from the tube and bring it as close as possible to a fully evacuated state. When a tube is not highly evacuated (because of some defect in manufacture, or deterioration during use), it is said to be *gassy*. The flow of current through a gassy tube may be erratic, and this can cause erratic operation. It is important to note that some gases remain after evacuation, being imbedded in the metal parts. To remove these imbedded gases, the tube elements first are brought up to red heat; then a *getter*, generally magnesium or barium, is flashed within the tube to absorb the gases released by the heat. The getter condenses on the inside surface of the tube envelope as a silver or reddish coating. The slightest air leak caused by a cracked glass envelope will result in a chemical reaction between air and the getter flash, turning it milky white. The tube interior is evacuated so completely that it approaches a nearly perfect vacuum. Fewer than half a trillion air molecules per cubic inch is considered a very efficient vacuum for receiving tubes.

16. Operation

a. It is necessary to review briefly several fundamentals concerning the behavior of the electron before proceeding with the explanation of the operation of the diode. The electron is a particle of negative electricity. It is attracted by a charge of opposite polarity and repelled by a charge of like polarity. Such behavior is in accordance with the basic laws of electricity which state that like charges repel and unlike charges attract. What is true about charges is true also about bodies or plates which are *charged positively* by the removal of electrons or *charged negatively* by the addition of electrons. Consequently, if a source of voltage, E, is connected between two facing plates, N and M, as in A of figure 20, with the positive terminal to N and the negative terminal to M, a difference of potential is established between N and M. This difference in potential equals the voltage source, E; in addition, plate N is positive relative to plate M, or plate M is negative relative to plate N. Finally, as the consequence of the redistribution of charges on plates N and M, an *electrostatic field* is created in the space between the plates.

b. As explained in TM 11–661, the direction of a line of force is the direction in which a positive test charge tends to move when placed in an electric field. Thus, because like charges ~~attract~~ and unlike charges ~~repel~~, a positive test charge tends to move toward a negative charge and away from another positive charge, or, from positive to negative. For this reason, the direction of the line of force is shown as leaving a positive charge and entering a negative charge. The choice of a positive charge as the test charge is conventional. Actually, if a negative

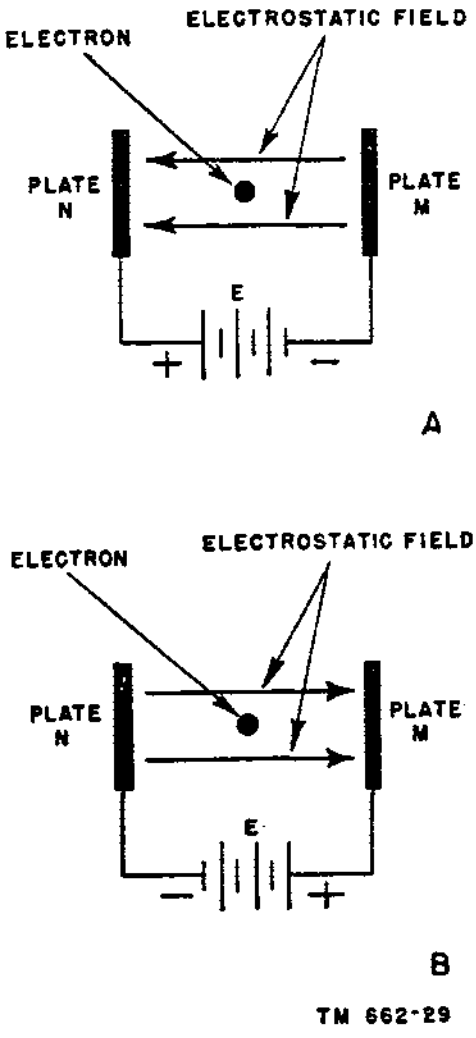


Figure 20. Electrostatic fields resulting from two plates and a battery.

test charge is chosen, the direction of the line of force will be reversed; that is, a negative test charge, when placed in an electric field, tends to move toward a positive charge and away from another negative charge, or, from negative to positive. Actually, it makes no difference whether a positive test charge or a negative test charge is selected because, in either case, the choice is arbitrary. The only difference is in the direction of the arrows on the lines of force in the illustrations. Throughout this manual, the use of a negative test charge is assumed and the direction of arrows on all lines of force in the illustrations are shown from negative to positive (A of fig. 20). This choice is a logical one because the study of vacuum tubes is concerned largely with the behavior of the electron in motion, and the electron, being a negative charge of electricity, always tends to move from negative to positive. Also, the electron tends to move in the same direction as the arrows on the lines of force, the latter being the graphical representation of the electric field.

c. No matter where the electron is placed in the field between N and M, it travels toward N along the lines of force. Only two lines of force are shown as a matter of convenience in the drawing; actually, the entire space between both plates is full of these imaginary lines of force. Although they issue from point charges, the radial arrangement of electrostatic fields shown for isolated charges is not used here. Great numbers of these charges are located on the two parallel plates and the effect of the forces caused by these charges within the space bounded by the two plates can best be shown by *parallel* lines.

d. If the connections of the voltage source are reversed so that plate M is joined to the positive terminal and plate N to the negative terminal, as in B of figure 20, the reverse condition is established. The electrostatic field still exists in the space between the two plates, but now the direction of the lines of force of the field is reversed. Plate M is positive relative to plate N and the electron advances along the lines of force toward M, the positively charged plate. The action of an electron in an electrostatic field of this kind can be described simply by saying that it advances along the lines of force to the most positive point in the field. In A of figure 20, this is plate N; in B of figure 20, it is plate M.

e. One factor that determines the intensity of the force of attraction and repulsion acting upon the unit test charge is the distance between plates M and N. The smaller the separation between M and N, the greater is the force of the field for a given value of applied voltage. If the applied voltage is doubled, the force of the field is doubled, and this has the same effect as reducing the distance between the plates by half. (Plate separation has the inverse effect with reference to the applied voltage.) Actually, the intensity of the electrostatic field can be increased by three methods: an increase in volt-

age applied to the plates, a reduction in the separation between the plates, and a combination of both of these methods. It follows that any increase in the intensity of the electrostatic field results in a strengthening of the force acting upon the electron. In effect, the greater this force, the more powerfully is the electron either attracted or repelled in its travel between the plates.

f. Another point of interest that might be mentioned is that, regardless of the number of electrons advancing under the influence of the field, their velocity per unit time is a function of the difference of potential established between the limits of the field. The greater the voltage on plate M relative to plate N, the faster the electrons travel through the field. If a great many electrons start from some point near N, the greater will be the number that will be able to advance to M in a unit time. The lower the difference of potential between the two plates, the lower the velocity of the electrons, and consequently, fewer electrons will span the field per unit time.

g. All of the preceding leads to the most important part of the review. It is evident that the direction of the electron advance is determined by the polarity of the field. If a source of electrons is assumed somewhere in the field, near plate N, and their behavior is examined relative to plate M, it is seen that the electrons will feel a force *attracting* them to plate M when that plate is *positive*, and will feel a *repelling* force when that plate is *negative*. Under one set of conditions, electrons will *advance* to plate M and under another set of conditions they will *not go to plate M*. The relationship between electron movement and the polarity of the field is basic to the operation of the diode and to all electron tubes.

h. As a preliminary explanation at this time and without attempting to deal with all of the pertinent points, reference is made to A of figure 21. This is an elementary version of a diode circuit. The emitter is indirectly heated. The voltage required to drive current through the heater is secured from a source normally identified as *heater voltage supply*. The polarity of the filament battery can be reversed, since its only purpose is to heat the filament. In the circuit shown it is a battery, but it can just as readily be a transformer of appropriate voltage and current rating operated from the a-c power line. The latter is the usual arrangement.

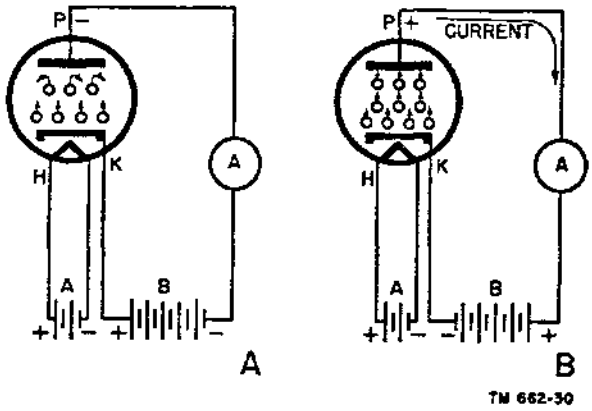


Figure 21. Different conditions of current flow through diode.

i. Apart from the heater circuit, the operating system consists of the emitter, in this instance the cathode, K, plate P, and the external circuit consisting of a *plate-voltage* supply source, B, and a current meter, A. The voltage applied to the plate is connected between the plate and the emitter. The purpose of the meter, which is connected in the circuit, is to indicate the behavior of the current. The plate battery is so connected as to make the plate *negative* with relation to the cathode.

j. At this point, it is important to understand a certain action inside the tube. Regardless of what may be connected between cathode and plate, or if no apparatus of any kind is joined to these electrodes, an electron cloud appears near the cathode as soon as the cathode is heated to electron-emitting temperature. This electron cloud is located in the *space* between the cathode and the plate. What happens to these negative charges? The answer is found in the discussion of charged plates earlier in this chapter. With plate P negative relative to cathode K, the emitted electrons are prevented from advancing to the plate; the direction of action of the electrostatic field between K and P repels the electrons. In the meantime, the continued heating of the cathode results in continued emission. The net result is a cloud of electrons in the space near the cathode, as illustrated by the tiny circles in A of figure 21. The absence of electron flow be-

tween cathode and plate makes the interelectrode space the equivalent of an open circuit; consequently, there is no current flow through the tube circuit formed by the cathode, the plate, the current meter, and the plate-voltage supply source.

k. In B of figure 21 the system has been modified by changing the polarity of the voltage applied to the plate, making the plate *positive* relative to the cathode. What happens to the emitted electrons under such polarity conditions? The previous discussion concerning the movement of negative charges in an electrostatic field furnishes the answer. The positively charged plate now exerts an attracting force on the emitted electrons. They advance across the space between cathode and plate. Since moving charges comprise electric current, the stream of electrons is the equivalent of an electric current without benefit of a wire conductor. The movement of these charges can be viewed conveniently as being from the cathode to the plate, thence through the meter, A, through the plate-voltage source, B, and back into the cathode, completing the circuit.

l. If it is assumed that the cathode is kept at an emitting temperature and the plate is maintained positive relative to the cathode, the movement of electrons continues through the circuit for as long as the aforementioned conditions prevail. Because the current flows to the plate in the tube and through the circuit elements joined to the plate, it is identified as *plate current*. The electrons shown in B of figure 21, now are seen to fill the space between the cathode and the plate.

m. This behavior of a diode leads to a number of important and far-reaching conclusions:

(1) Current flow in a diode occurs only when the plate is positive relative to the electron emitter.

(2) Current will not flow in a diode when the plate is negative relative to the electron emitter.

(3) Current flow in a diode can be in *one* direction only, from cathode to plate, never from plate to cathode. This action is called *unidirectional or unilateral* conduction.

(4) A diode can behave like a control valve, automatically starting and stopping current flow.

n. These capabilities lead to many different applications of the diode, several of which are detailed elsewhere in this manual. One of these can be appreciated here. If the plate battery in B of figure 21 is replaced by an a-c voltage source, which alternately changes the polarity of the plate and the cathode, the tube will alternately conduct and cease conducting. Each time the plate is made positive, current will flow through the system and continue flowing until the polarity of the plate is changed to negative, at which time, current flow through the plate circuit will cease. This is the principle of *rectification.*

o. The fact that two diode systems are contained within a single envelope does not modify the behavior. Each diode behaves as outlined. The use of two diode sections is a matter of accomplishing certain results conveniently. These will be explained later.

17. Space Charge

a. The statements made thus far in regard to the electrons emitted from a cathode (or filament) and the statements made concerning the plate voltage as well as the plate current may well be considered more critically. How much electron emission is possible? How much plate current is possible or permissible? How high can the voltage on the plate be? These questions deserve answers because they influence the understanding of the over-all operation of the device. This leads to the subject of *space charge.* In order to make this manual easy to read, the cathode and filament types of electron emitters will be treated in like manner. Their physical differences are taken for granted, but it is necessary to select one or the other term for easiest reference to emitters. Accordingly, the word *cathode* will be used to denote the electron emitter in all cases, unless otherwise specifically stated. It will have meaning only as a source of electrons, rather than as a term which distinguishes indirectly heated emitters from directly heated emitters.

b. The number of electrons which traverse the space between the cathode and the plate in

a diode per unit time (in other words, the plate current), is determined by four important factors:

(1) The temperature of the cathode;
(2) The emission per unit time;
(3) The voltage of the plate relative to the cathode;
(4) The space charge.

c. Items (1) and (2) are related to each other because the temperature of any cathode determines the number of electrons emitted per unit time. Logically, a supply of electrons is necessary in order that plate current flow may exist.

d. Item (3), the plate voltage, is another important factor. It is the force attracting the emitted electrons. At first thought, it would seem as if a very low value of positive plate voltage would immediately attract all the electrons which have been liberated by the cathode. This does not happen because of item (4), the space charge. The space charge is responsible for the control of plate current. As a matter of fact, plate current in diodes generally is described as being *space-charge limited,* and an analysis of the behavior of the space charge explains why changes in the value of voltage applied to the plate change the value of plate current. The term *space charge* refers to the *effect* of the electrons which have been liberated and which accumulate in the neighborhood of the cathode, with or without plate-current flow in the tube.

e. Imagine for a moment a tube arranged as illustrated in A of figure 22. The cathode is heated to an electron-emitting temperature and the plate is joined to the cathode. Since no voltage is applied to the plate, it exerts no attracting force on the emitted electrons. If the cathode is emitting electrons, what happens to them? As a beginning, it is necessary to make several assumptions. The heat applied to the cathode imparts sufficient velocity to the electrons to enable them to overcome the work function of the emitter material. They break through the potential barrier. But most of the energy possessed by the electrons is given up in passing through the potential barrier and very little is left after they leave the emitter. This is the first assumption: The electrons are considered as leaving the cathode at a relatively low velocity. A few emitted electrons can possess sufficient velocity to complete the excursion to the plate, without any attracting pull from the plate. These are so few in number that they can be disregarded in terms of normal functioning of the tube.

f. The second assumption is that the shape of the emitting surface of the cathode is a straight side or a plane surface. The third and final assumption is that the electrons leave the cathode in an orderly manner and have orderly motion, something like the movement of troops in columns. This is not really true because emission is haphazard and in random directions away from the surface, but the assumption does no harm. An idea of what is meant is illustrated in B; the disposition of the electrons is shown more accurately in A. The orderly emission aids the understanding of what follows. Let us start with the emission of the first row of electrons, in B. They have nothing in front of them to impede their progress. However, their low velocity of emission is a limiting factor, and they do have to contend with the second row in back of them, the third group in back of the second, the fourth group in back of the third, and so on. Since the basic law of charged bodies states that like charges repel one another, the electrons back of the first group are experiencing a repelling force exerted by the electrons in front of them, and the direction of this force is such as to retard the motion of the electrons in their advance away from the cathode.

g. Layers after layers of electrons feel these forces acting on both sides of them and, while they do move under the velocity of emission, the net result is a *cloud of electrons near the cathode.* The density of this cloud is greatest near the cathode, and less and less dense away from the cathode, as in A. To complete the picture, it is necessary to consider two other points. Since each charge in space exerts an influence upon each neighboring charge, the accumulation of the charges in space gives rise to an accumulative effect of great importance. This is the condition created in the proximity of the cathode. It is spoken of as the *space charge.* Actually it is an electrostatic field that exists between the boundary of the electron cloud facing the cathode and the emitting surface of the cathode, as shown in C.

h. One limit of this electrostatic field is the number of charges and the other is the emitting

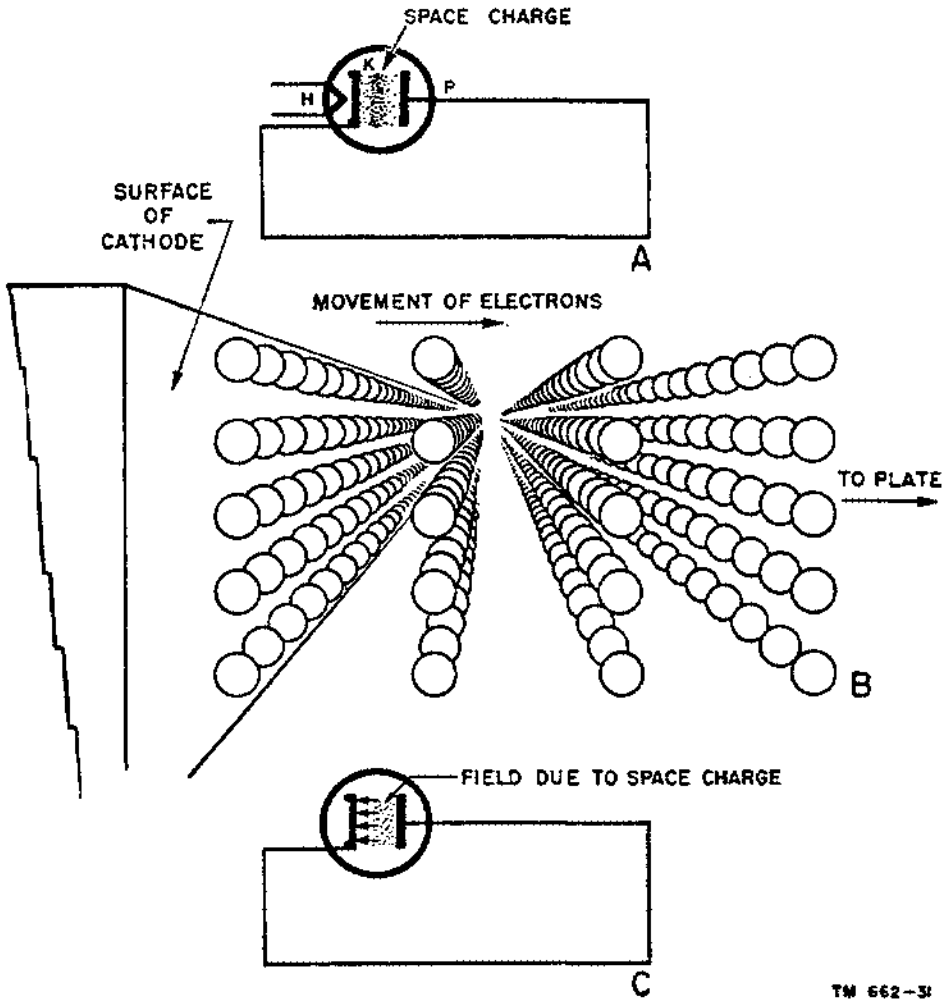


Figure 22. Electron accumulation in diode.

surface of the cathode. The direction of the lines of force in terms of emitted electrons is away from the electron cloud. The cathode surface, on the other hand, is assumed to be the positive boundary of the field, because as each electron leaves it during emission, the cathode contains one additional positive ion (an atom lacking one or more electrons) and tends to attract electrons back into itself. It might seem that the density of the space charge will increase as long as the cathode is emitting electrons. Such is not the case. For any one given temperature of the cathode, the emission of electrons is definitely limited, as is the *density* of the space charge. The reason for this is the repelling action of the space charge. Having acquired a critical density, the space charge develops a field of such intensity as to *repel back into the cathode one electron for every electron which enters the electron cloud.* This condition of equilibrium in the space charge is called *emission saturation.*

i. Every value of cathode temperature has a condition of emission saturation. This is understandable because an increase in cathode temperature increases the velocity of the emitted electrons and these new electrons will enter the space charge and make it more dense. After the density has been increased to the point where the field strength can offset the increased velocity of the emitted electron, a new level of emission saturation is reached for the new cathode temperature. It is evident, therefore, that the space charge has a *controlling influence upon*

the emission of electrons from the cathode. The control exerted by the space charge on the plate current can be seen by reference to figure 23. The positive plate voltage is applied to that electrode, giving it a positive charge. The plate is positive relative to the cathode, but in between these two electrodes is the space charge with its retarding influence on the emitted electrons. the field created by the voltage applied to the plate. The field between the space charge and the cathode is treated separately. The movement of an electron between cathode and plate can, therefore, be viewed as being first into the space charge and then out of the space charge to the plate. In this way equilibrium or constant electron density is maintained in the space

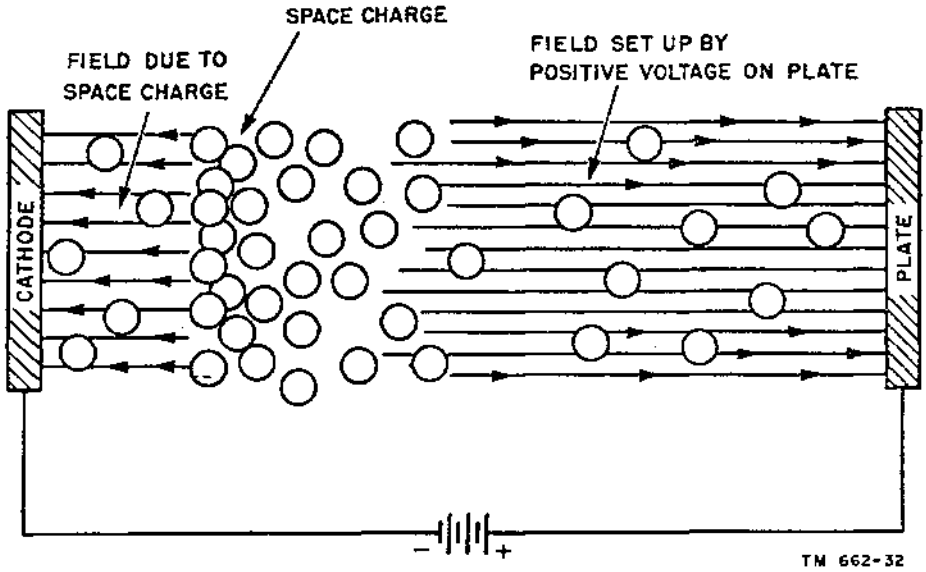


Figure 23. Electrostatic fields present between cathode and plate as result of space charge.

j. Two electrostatic fields are, therefore, present between the cathode and the plate: one between the cathode and the space charge and the other between the space charge and the plate. Because of the presence of the space charge, it is entirely proper to view the attracting force of the positively charged plate as acting on the electrons in the space charge, rather than directly on the electrons being emitted.

k. The reason for this is as follows: The lines of force going to the positively charged plate represent a certain number of excess positive charges on that plate, and, naturally, a deficiency of a certain number of negative charges. The location of sufficient negative charges to serve as terminations of the lines of force going to the positive plate is unimportant. Although it is true that the plate voltage is applied between the plate and the cathode, the electron cloud (space charge) located in space between these two electrodes furnishes the number of negative charges required as terminations for charge. If the equilibrium in the space charge is disturbed by removing electrons from the portion that is nearer the plate because of the attracting power of the positive voltage on the plate, it results in a reduction of the magnitude of the field of the space charge. Its ability to repel electrons emitted from the cathode is, therefore, reduced, and consequently only that number of electrons required to restore equilibrium will be added to the space charge in the zone near the cathode. More than this number will not be added to the space charge, because the state of equilibrium must be maintained. If electrons equal to 10 ma (milliamperes) of current are removed from the space charge per second, that many electrons will enter the space charge from the cathode each second. The movement of electrons is from the cathode into the space charge, through the space charge, and out of the space charge to the plate *without altering the density of the space charge.*

l. A directed movement of electrons in this manner can be described as being the flow of plate current between the cathode and the plate, thence through the remainder of the system. It is permissible to view the space charge as a reservoir of electrons, from which are drawn the negative charges which are required to equal the instantaneous plate current. The cathode is the supply which replenishes the space charge. This is similar to a water-supply system in which the consumers draw water from a local reservoir, and a stream or lake automatically supplies the equivalent amount of water required to maintain a predetermined level.

m. For a given value of plate voltage and a constant cathode temperature, a fixed number of electrons are drawn from the space charge per unit time. This results in a plate current of a certain value which is measured in amperes. A *change* in plate voltage *changes* the rate of electron flow and the *plate current* likewise changes to an extent determined by the direction of change in plate voltage. At a sufficiently high positive plate voltage, all the emitted electrons enter the space charge because that many leave the space charge. Then the *plate current* is equal to the *emission current*, by which is meant the total number of electrons emitted by the cathode per unit time.

n. The space charge performs a useful and necessary function. In most tubes, the cathodes (or filaments) are designed to emit a surplus of electrons so that more of them are available than are actually required during each unit time. If there were no space charge, even a very low positive plate voltage would result in very high values of current and short emitter life. Some kind of control is, therefore, desirable, and this is exerted by the space charge. Hence the statement that plate-current flow in diodes (and other electron tubes) is *space-charge limited.*

18. Vacuum-tube Characteristics

To study more adequately the various factors affecting diode and other tube types, this discussion of vacuum-tube characteristics is of fundamental importance.

a. In a vacuum tube, a definite relationship exists between plate voltage and plate current —that is, between the magnitude of the attracting force exerted by the positively charged plate and the number of electrons attracted to the plate. There is also a relationship between emitter temperature and electron emission—more specifically, filament emission and filament current—and between cathode emission and heater current.

b. The manner in which these variable factors influence a vacuum-tube operation establishes the characteristics of the tube, and this is most clearly illustrated by means of graphs known as *characteristic curves.* As will be shown, these curves provide useful reference data for studying tube performance, and also for predicting performance under particular conditions of operation.

c. For simplicity, characteristic curves can be regarded as being charts of *cause and effect.* Characteristic curves are plotted within the boundaries of two reference lines: one, a vertical reference line called the *vertical axis,* the *Y-axis,* or the ordinate; the other, a horizontal line called the *horizontal axis,* the *X-axis,* or the abscissa (fig. 24). These two reference lines serve as scales upon which can be indicated the units of measures (volts, ohms, amperes, and so on), representing variations in the dependent variable (effect), and the units of measure (volts, ohms, amperes), representing variations in the independent variable (cause).

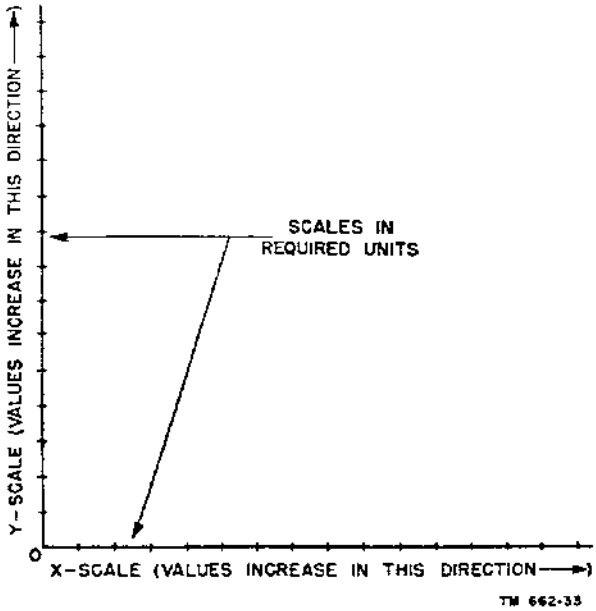


Figure 24. Organization of chart on which tube characteristics can be drawn.

d. Generally, changes in the magnitude of the *cause* (X-axis) are shown on the abscissa, and changes in the magnitude of the *effect* (Y-axis) are shown on the ordinate. These scales of magnitude usually, though not always, start at the junction of the two axes, the 0 point. The units indicated depend on what information is to be conveyed.

e. The characteristic curve (or curves, for there can be more than one), appears inside the space bounded by the two axes (heavy line in fig. 25). The characteristic of a device also is shown in the figure. Its description is unimportant; all that matters is that the characteristic curve displays cause and effect: The current (in milliamperes) through the device varies for different applied voltages (in volts). Current is effect, and voltage is the cause. The effect is shown on the Y-axis in steps of 1 ma and the cause is shown on the X-axis in steps of 2 volts. What is the current corresponding to a voltage of 10 volts? A projection upward from the 10-volt point on the voltage scale meets the Y-axis or current scale at 5.6 ma. This is the amount of current corresponding to 10 volts.

f. To establish the effect of a change from a known reference value, assume that the current corresponding to 24 volts is required. Repeating the previously described process, but starting at the 24-volt point on the voltage scale, leads to a new current value of 10.6 ma. Consequently, a change of 14 volts (from 10 to 24 volts) means a change of 5 ma.

g. Finally, simultaneous projections can be made from both axes, for various magnitudes of whatever is indicated upon the abscissa and the ordinate. These intersect, establishing points from which a characteristic curve *can be drawn* that will identify the relationship between the quantities indicated upon the reference axes. Several examples appear later.

h. In general, characteristic curves involve two variable factors. These have already been indicated, in terms of *cause* and *effect*. The characteristic curve for this relationship is termed the *plate-current plate-voltage characteristic* curve, or the I-E curve. Similiarly, if the curve illustrates the cathode temperature for varying heater current, it would be called the *cathode-temperature heater-current* characteristic curve, since it is the change in heater current that causes the variation in cathode temperature.

i. Characteristic curves operate in both directions. If the curve is viewed as the expression of the cause and its resultant effect, the effect resulting from a change in the cause can be

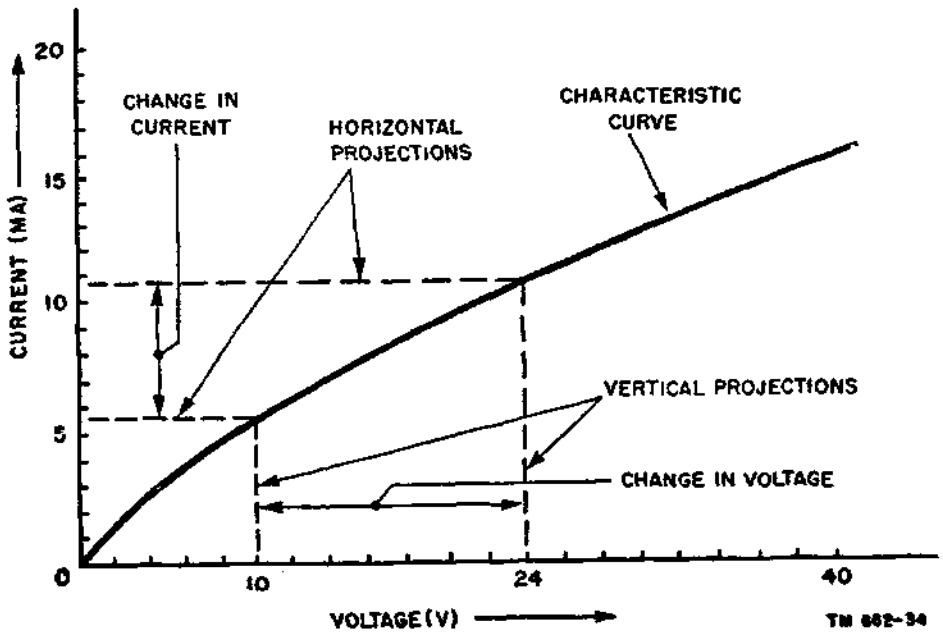


Figure 25. Plot of simple characteristic curve.

noted. It is also possible to regard this curve in another fashion. It may be desired to know what change must be made in the primary variable in order to produce a definite condition in the second variable. Consequently, a plate-current plate-voltage curve can be examined to ascertain the plate voltage that is required to produce a certain plate current, rather than the effect upon the plate current by a certain change in plate voltage. In other words, the curves operate with equal facility in two ways, one being the resultant change in effect as the cause is varied, and the other being the required change in cause to produce a certain change in effect.

j. Although characteristic curves illustrate the relationship between two variables, a third quantity usually is associated with them. For example, in the I-E curve, it is necessary to state the temperature of the cathode, the current through the filament or heater wires, or the voltage applied to the filament or heater wires. If no information is given regarding the cathode temperature, current flow, or voltage, the characteristic could not be identified as applying to any *particular* condition. For, while the curve can be representative of behavior, the exact values of plate current indicated mean nothing unless the exact conditions producing the state of behavior are identified. At least three values are indicated on or required for a vacuum-tube characteristic curve: the two variables illustrated in the curve, and a third, each indicating the exact condition contributed by the other factors to the information illustrated in the characteristic curve.

19. Linear and Nonlinear Characteristics (fig. 26).

a. Two terms often encountered in descriptions of characteristic curves are *linear* and *nonlinear*. The meaning of the first term is graphically illustrated in A of figure 26. For example, if a d-c voltage is applied across a fixed resistor, the relationship between the voltage (one quantity) and the current (the second quantity) is a straight line. The resultant change in the second quantity (current) is *directly proportional* to variations in the first quantity (voltage). Such a relationship is said to be *linear*, and it appears as a straight line over the full range of variation. In this case, the term *curve* is not truly descriptive of the straight line. However, not many characteristic curves of vacuum tubes are linear throughout their length.

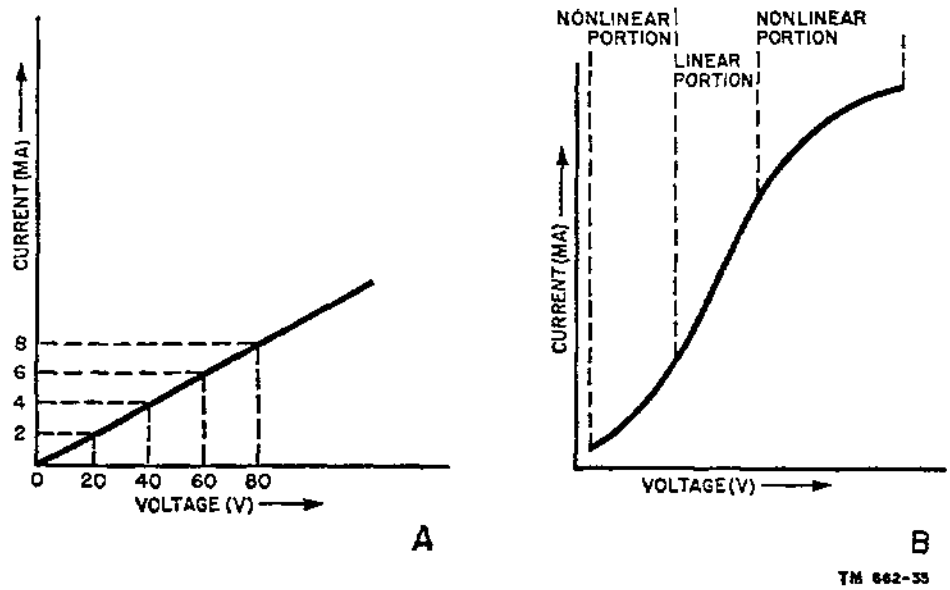


Figure 26. Linear and nonlinear characteristic curves.

b. B of figure 26 shows a tube characteristic curve which resembles the type found frequently. The characteristic is *nonlinear* over a region, representing a range of applied voltage, then becomes linear over another range of voltages, and again becomes nonlinear. Just why this is so is unimportant; the importance lies in recognition of the meaning of linearity and nonlinearity. The reason for this is frequent reference to operation over the linear portion of a tube characteristic. These are specific conditions of use.

c. At all times, linear operation means *direct proportionality* between a cause and an effect, as illustrated in A of figure 26, where a two-time increase in voltage, from 20 to 40 volts, causes a two-time increase in current, from 2 to 4 ma. Only a straight-line characteristic is a linear characteristic. This can be the entire characteristic curve or a part thereof, as indicated in B of figure 26. The completely nonlinear characteristic is shown in figure 27. At no point is one variable directly proportional to the other.

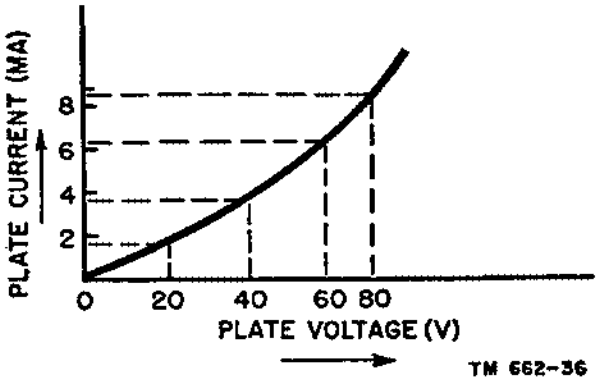


Figure 27. Curve illustrating completely nonlinear characteristic.

20. Static and Dynamic Characteristics

Linear and nonlinear characteristic curves can be of either the *static* or the *dynamic* type. Both static and dynamic characteristic curves exist for each vacuum tube. They differ in shape as well as in the actual values they represent. A simple explanation of the difference between these two types of curves is that, in *static* characteristics, the values are obtained with different d-c potentials applied to all the tube electrodes, and the organization of the system is not typical of actual operation. The *dynamic* characteristics are the values obtained when the organization of the system conforms with typical operation. This is explained more fully later.

21. Family of Curves

a. Several characteristic curves usually are shown together, to illustrate the relationship between the same two quantities under different conditions. A group of such curves is known as a *family.* Figure 28 is a family of different plate-current plate-voltage curves for different values of cathode temperature. For a given value of plate voltage, the plate current will be maximum at curve A. Therefore, curve A indicates the highest cathode temperature, curve B shows a decrease in cathode temperature, and the temperature is the least for curve C. Numerous families of curves appear in later sections of this book.

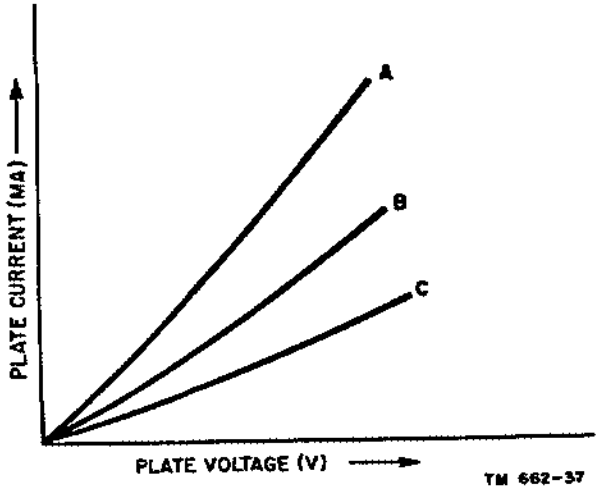


Figure 28. Family of plate-current plate-voltage curves for three values of cathode temperature.

b. The characteristic curve, or family of curves, usually encountered in vacuum-tube literature relates to the flow of plate current in the tube. The most common, and perhaps the most important of vacuum-tube characteristics, is the one illustrating the magnitude of the electron stream arriving at the plate for various values of positive voltage applied to the plate—namely, the plate-current plate-voltage char-

acteristic. Most vacuum-tube applications are judged in terms of the plate current, since it is by the flow of plate current through the tube and the different electrical devices externally connected to it that the various capabilities of the tube can be utilized.

22. Plate-current Emitter-temperature Characteristic

(fig. 29)

To investigate the manner in which the emitter temperature and the space charge influence plate current in a diode, a circuit is set up in which different values of emitter temperature can be created by varying the heater or filament current while the plate voltage is held constant.

a. In A of figure 29, a fixed filament voltage source, A and a variable resistor, R, allow changes in the heater current. The filament meter indicates the current in this circuit. I_f indicates the flow of filament current and E_f the voltage across the filaments. The plate voltage is supplied by battery B and the plate current is read on the meter in the plate circuit. I_b indicates the flow of plate current. It might be well to mention that the capital letter I for current indicates constant, average, or rms (root mean square) values by appropriate subscripts. Instantaneous values are indicated by a small letter i for current and e for voltage. Constant, average, or rms values of voltage are indicated by the capital letter E with appropriate subscripts. The subscript letter f in figure 29 indicates the filament, whereas the subscript b near the plate-current meter associates it with the plate. Common usage has established

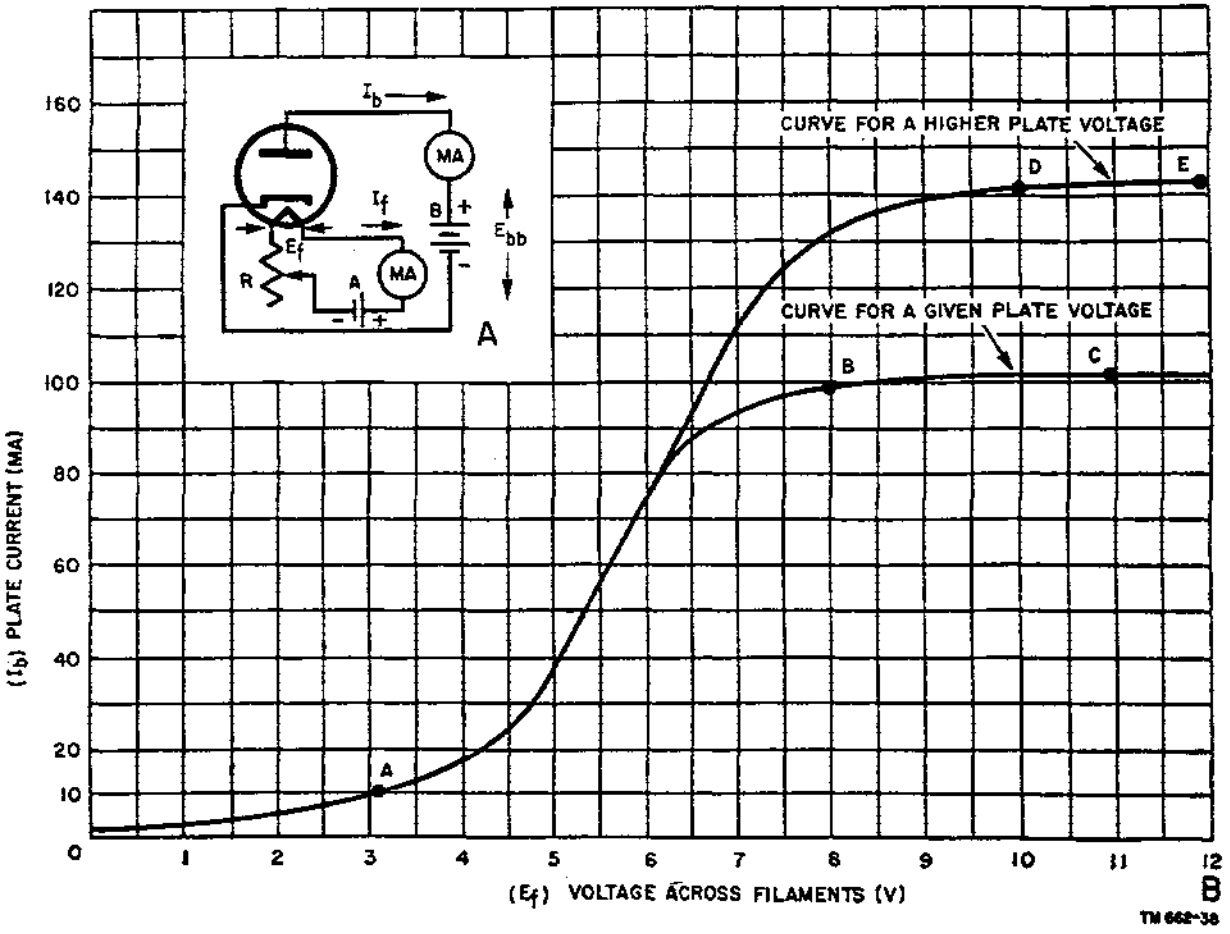


Figure 29. Plate-current filament-voltage characteristic curves.

E_{bb} as the voltage of the plate voltage supply. These subscripts are further explained in chapter 4.

b. The general contour of the $I_b = E_f$ curve can be predicted from what has already been said about the conditions of emission. The curve of filament voltage versus plate current, with fixed plate voltage, would start at 0 corresponding to the 0 value of filament voltage. Then it would rise as the voltage is increased. Eventually it would flatten when the emission saturation points (B and D of fig. 29) would be reached for the applied value of plate voltage. Beyond this value of filament voltage, the increased emission contributes little to the plate current (lines BC and DE), since the number of electrons pulled out of the space charge by the plate voltage is not increased. Only the density of the space charge is increased. As is evident in the graph, a slight rise in plate current occurs with increased filament voltage beyond emission saturation, but this increase is so slight, relative to the change in plate current up to the saturation point, that it can be disregarded for all practical purposes.

c. Referring to curve ABC (B of fig. 29), the span A-B represents current limited by cathode emission for the existing plate voltage. Between points B and C on curve ABC the limitation of plate current is due to the action of the space charge. A means of raising the plate-current limitation is by reducing the effectiveness of the space charge. This can be done most simply by raising the plate voltage.

d. Raising the plate voltage results in a rise of the plate-current curve, and a new value for the point of emission saturation or the start of the space-charge-limited plate-current area. This is shown as curve ADE. Consequently, it can be seen that, for every value of plate voltage, there is a limit to the number of electrons which can be drawn over to the plate in unit time to form the plate current. For the two curves, these are points B and D. The point at which emission saturation is reached is also known as the *saturation point*, and the maximum current flowing (as BC and DE) is known as the *saturation current.*

23. Plate-current Plate-voltage Characteristic

a. Another important relationship is that between the voltage applied to the plate and the resultant plate current when the emitter temperature is held constant. This approaches the conditions under which the tube is used. The circuit for developing these data is shown in A of figure 30. A voltage source, B, applies a voltage between cathode and plate through a current meter, I_b. The voltage applied to the plate of the diode is shown on a voltmeter and is labeled E_{bb}. The subscript letters bb associate voltage E with the source—namely, the battery, B. The meter labeled I_b indicates the plate current flowing in the system.

b. The diode in A of figure 30 is shown without a heater and its associated current source. It is common practice to do this when illustrating the circuity of simple, indirectly heated tubes. The presence of the heater is assumed. If this were a filament-type tube, the circuit would appear as in B of figure 30. Since the emitter temperature is not a variable, the heater or filament circuit is not indicated.

c. If curve ABC shown in C of figure 30 is examined, it will be noted that a fairly rapid rise in plate current occurs as the plate voltage is increased from the 0 value. Then the increase in plate current becomes less rapid, with uniform increases in plate voltage until a point, B, is reached where very little increase in plate current occurs as the plate voltage is increased still more. Point B represents the condition when *all of the emitted electrons* are admitted into the space charge to form the plate current. Between points A and B, the plate current is limited by the space charge; between B and C, it is limited by the emission. Consequently, in the example shown, raising the plate voltage from 0 to 350 volts increases the plate current from slightly above 0 to about 68 ma. Raising the plate voltage from 350 to 500 volts causes an increase of only 2 ma from 68 to about 70 ma. The explanation for the presence of a very slight amount of plate current with 0 plate voltage is the fact that some of the electrons are emitted from the cathode with such high velocity that they advance across the space between the emitter and plate without benefit of any attracting force issuing from the plate.

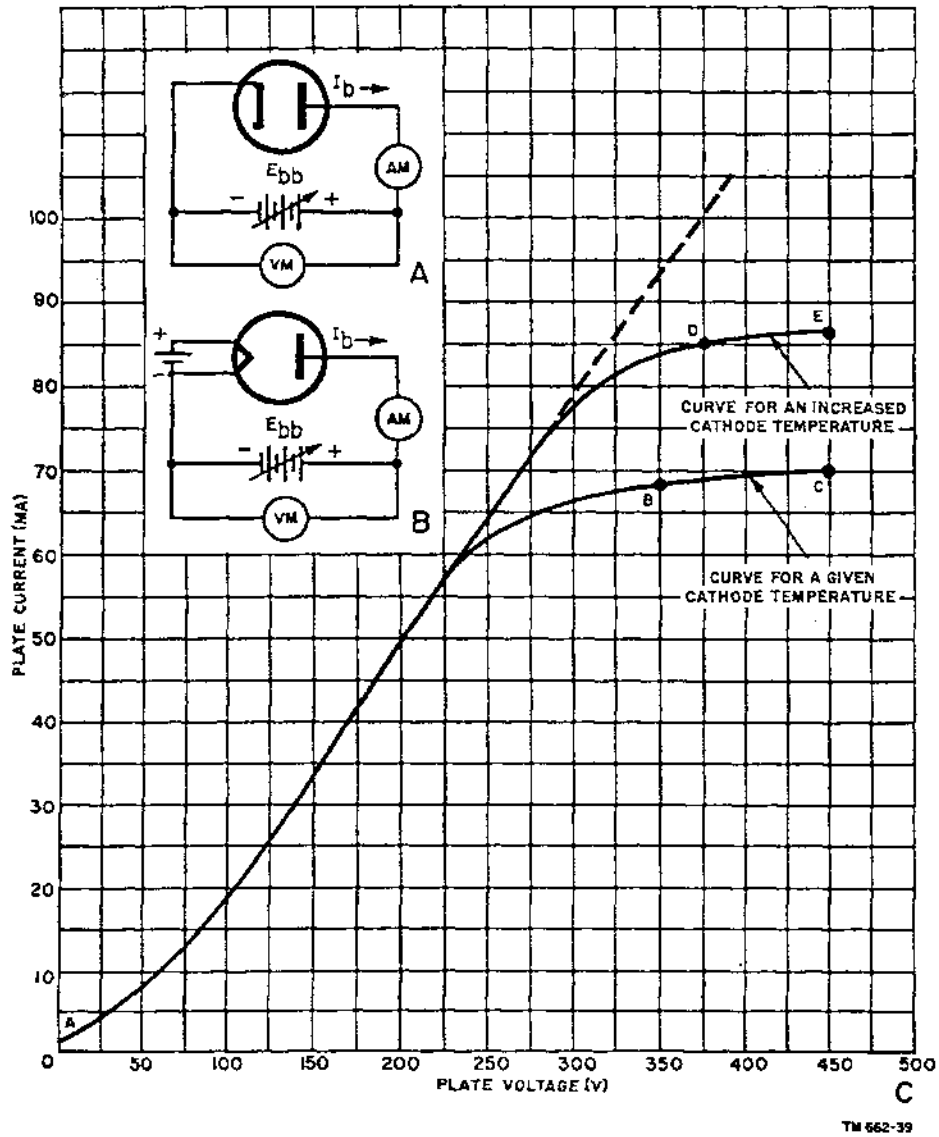


Figure 30. Plate-current plate-voltage characteristic curves.

d. To obtain an increase in plate current for plate voltages in excess of 350 volts, it is necessary to provide a greater flow of electrons. This can be accomplished by raising the emitter temperature. Assuming an increase in cathode temperature, a curve similar to ADE might be obtained. The plate-current saturation point D corresponds to a plate-current flow of about 85 ma (in contrast to the previous 68 ma at point B) and a plate voltage of about 375 volts. Any further increase will not produce a substantial increase in plate current.

e. The discussion thus far reveals that, for every tube operated at a fixed emitter temperature, there is a certain value of plate voltage beyond which it is useless to increase the voltage further, since all of the emitted electrons are moving over to the plate, and consequently, no appreciable plate current increase can be obtained. However, one factor remains: There is a difference in saturation points depending on whether a tungsten, a thoriated-tungsten, or an oxide-coated cathode is used. The curve in C of figure 30 was obtained with a diode having a tungsten filament. Figure 31 shows that the emission from an oxide-coated emitter is

considerably larger, since the plate current is larger, than that of the tungsten types. Oxide-coated emitters release so many electrons that it is practically impossible to find plate voltages which will draw off all of these electrons without ruining the tube. Consequently, most modern tubes which use oxide-coated cathodes do not display a plate-voltage saturation characteristic, but rather show continually rising plate-current curves as the plate voltage is increased as shown in figure 31. Note from the curves that as the operating temperature of the cathode increases, the plate current increases. In addition, this increase will have a more noticeable effect on the oxide-coated cathodes since the solid and dashed lines are much farther apart in the higher operating temperatures than in the lower ones.

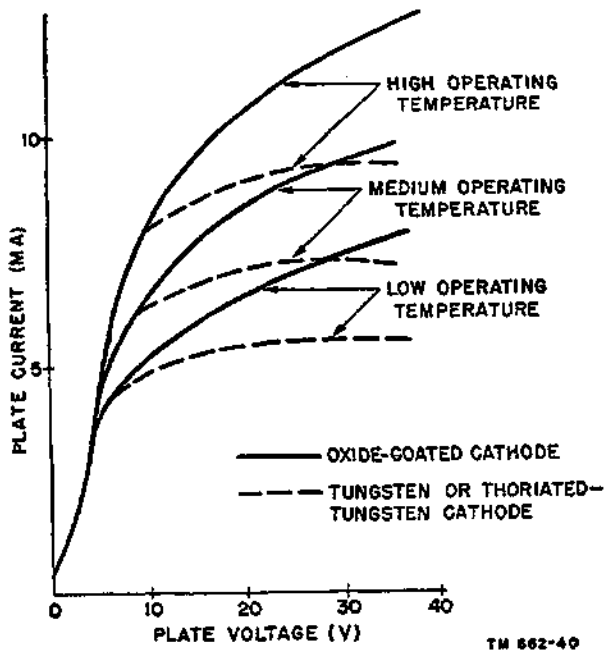


Figure 31. Plate-current emitter-temperature characteristic curves of diode with different types of emitters.

24. D-c Plate Resistance of Diode

a. Since the application of a positive voltage to the plate of a diode results in the flow of plate current, and since some form of control of the magnitude of plate current for different values of voltage exists in the tube, it is entirely proper to view the current control mechanism, whatever may be its nature, as being the equivalent of a resistance. Electrical fundamentals teach that the control of current in a system issues from some form of opposition to the current flow present in the system.

b. Such opposition exists in all electron tubes, among which is the diode. It stems from many factors, such as the spacing between the electrodes, their physical size, the conditions of emission, the conditions of the space charge, and, in general, the energy wasted while the electrons are traversing the space within the tube. Tube resistance is of two kinds: *d-c plate resistance* and *a-c plate resistance*, each of which will be explained. The former usually is symbolized as R_p and the latter as r_p.

c. The d-c plate resistance of the diode is that opposition to plate current flow offered by the tube when a d-c voltage is applied to the plate. It can be calculated from Ohm's law, $R=E/I$, with the plate voltage and the plate current inserted as the known factors in the equation.

d. Referring to figure 32, B shows a typical plate-current plate-voltage characteristic for a type 6H6 duo-diode tube, using only one pair of the two pairs of elements contained inside the envelope—that is one cathode and its associated plate. With 8 volts dc applied to the plate, in A, the plate current, I_b, is seen to be 10 ma, or .01 ampere. (The notation E_b is used as the varying constant voltage between the plate and cathode. This may or may not be the same value as E_{bb}.) Applying Ohm's law for d-c circuits, these values of plate voltage and plate current represent a d-c plate resistance of

$$R_p = \frac{E_b}{I_b} = \frac{8}{.01} = 800 \text{ ohms.}$$

e. Similarly, with 20 volts dc applied to the plate, the curve shows a plate current of 40 ma, or .04 ampere. This corresponds to a d-c resistance of 20/.04 = 500 ohms. With 28 volts dc applied to the plate, the plate current on the curve is 66.4 ma or .0664 ampere, and the d-c resistance is 28/.0664 = 422 ohms.

f. Examination of these figures, and also of the shape of the characteristic curve, shows that the resistance offered by the diode to the flow of plate current is *not* constant, as is ordinarily the case when resistance is present in a conventional d-c circuit. The characteristic shows that the resistance of the diode *decreases*

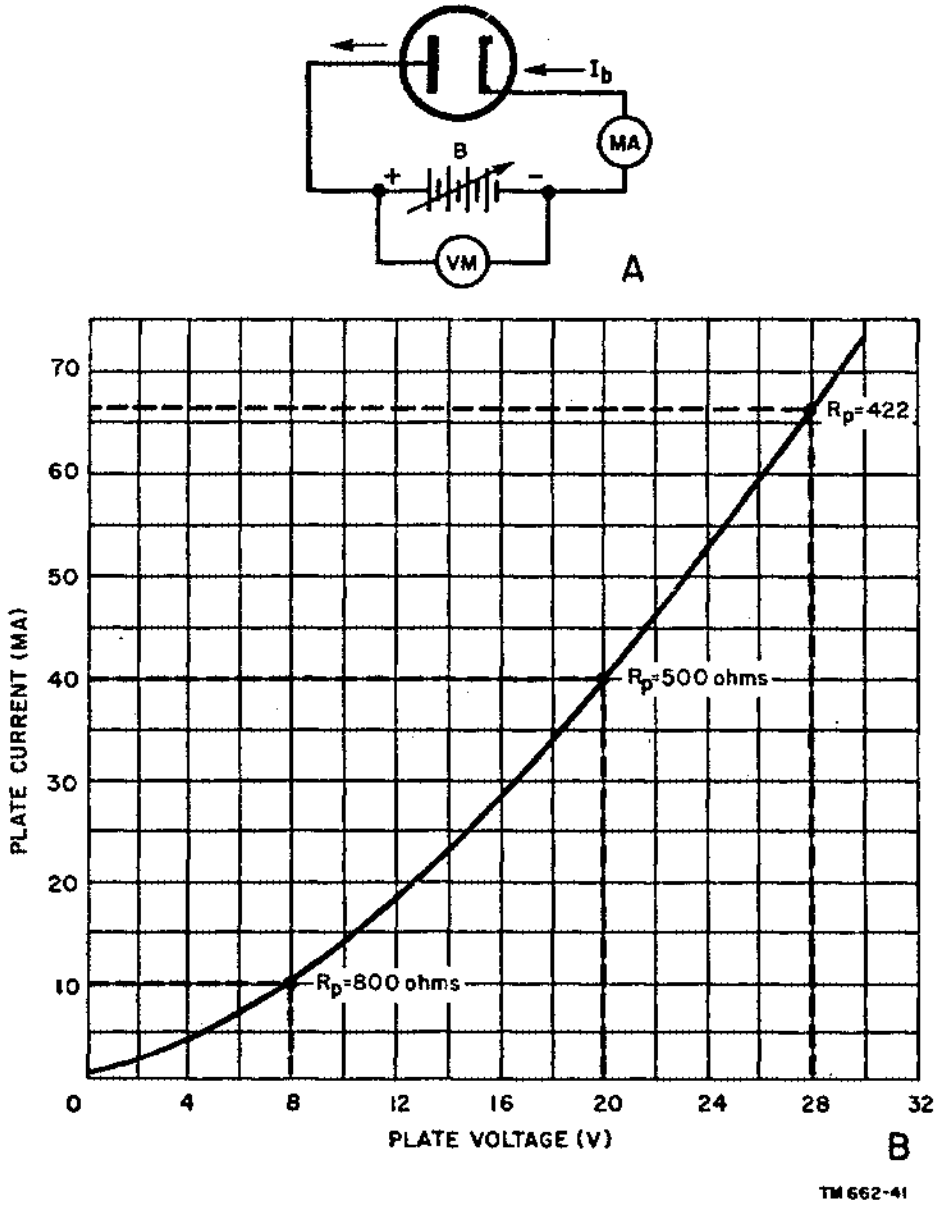


Figure 32. Plate-current plate-voltage characteristic for type 6H6 tube, using only one diode section.

as the plate voltage increases, and *increases* as the plate voltage is decreased. It has a nonlinear behavior. If the relationship of plate voltage and plate current were linear over the entire range of plate voltage, the plate-current curve would be a straight line instead of having a curved characteristic. A straight line would indicate that the d-c plate resistance remained constant over the full range of plate voltage.

g. Another significant fact in connection with the $E_b = I_b$ characteristic curve is the condition resulting when the two sections of this duo-diode are connected in parallel, and the two cathodes also are joined in parallel. The plate current in this case becomes twice the amount obtained when the same value of plate voltage is applied to a single pair of elements. Accordingly, the values at any point along the plate-current curve are doubled when both sections of the duo-diode are paralleled. The plate resistance, therefore, becomes half of that existing

when one pair of the two diode portions is used. This will be found to be true in all multiple-section diodes.

h. The absence of plate-current saturation points similar to those appearing in figures 29 and 30 is due to the use of oxide-coated emitters in this tube. An application as low as 32 volts to the plate results in a fairly high value of plate current, almost 70 ma. Judging by the shape of the characteristic, the saturation point is a long way off. The tube probably would be damaged long before the plate-current curve would flatten because of the application of sufficient plate voltage to attract all the emitted electrons. This does not mean that diodes are not used at plate voltages exceeding 32 volts; they are used with very high voltages, many tens of thousands of volts, but when so used, diodes are specially designed.

25. A-c Plate Resistance of Diode

a. The a-c plate resistance of the diode is defined as the resistance of the path between cathode and plate to the flow of *an alternating current* inside the tube. Such is the definition meant when the term *resistance* is used without qualification for the diode and all other electron tubes. As will be seen later, it is an important term and is closely related to operating conditions.

b. The a-c plate resistance is the ratio of a small change in plate voltage by the corresponding change in plate current. Expressed in an equation

$$r_p = \frac{\Delta e_p}{\Delta i_p}$$

in which r_p is the a-c plate resistance in ohms, Δe_p represents a small change in plate voltage, and Δi_p represents a corresponding small change in plate current caused by the plate voltage change. The Greek letter Δ signifies a *small change of.*

c. Figure 33 shows a plate-current plate-voltage characteristic curve identical to the one in B of figure 32 and obtained from the circuit in A of figure 32, where one section of a 6H6 diode is used. To establish the *a-c resistance* at any point along the curve, the plate voltage is varied on both sides of it at some definite value. B of figure 32 shows that the d-c plate resistance, R_p for this diode is 500 ohms when the plate voltage is held constant at 20 volts dc. Suppose it is desired to find the a-c resistance when the mean value of this assumed a-c voltage is 20 volts, and the variation or *swing* is arbitrarily chosen at 1.6 volts on either side of the 20-volt point; that is, when Δe_p equals 3.2 volts (fig. 33).

d. To compute r_p, the change in plate current for the given change in d-c plate voltage first must be found from the curve. At 21.6 (20 plus 1.6) volts, the plate current is 45 ma or .045 ampere. At 18.4 (20 minus 1.6) volts the plate current is 35 ma or .035 ampere. These provide the two limits of voltage and current. Consequently,

$$r_p = \frac{\Delta e_p}{\Delta i_p} = \frac{21.6 - 18.4}{.045 - .035} = \frac{3.2}{.010} = 320 \text{ ohms.}$$

e. The value of 320 ohms given above is the a-c plate resistance for a plate voltage which varies between 18.4 and 21.6 volts, whereas the same point is equal to a d-c plate resistance of 500 ohms when the plate voltage is held constant at 20 volts. Using the same method, 278 ohms a-c plate resistance is obtained at the 28-volt plate-voltage point for a change in plate voltage of 1.6 volts each side of the mean value of 28 volts, whereas the d-c resistance is 422 ohms when the plate voltage is maintained constant at 28 volts. Similarly, r_p is shown equal to 527 ohms when the 8-volt plate-voltage point varies *1* volt on either side of the 8-volt mean value. If 1.6 volts is used in the latter case instead of 1 volt, r_p still remains relatively close to 527 ohms. However, it must be kept in mind that the smaller the change in plate voltage, the more accurate are the results. This is because of the nonlinearity of the characteristic curve about this small change. In the former two cases, the curve is fairly linear and 1.6 volts are used arbitrarily. Normally, for linear operation, the operating point for this curve is chosen with an r_p equal to about 320 ohms.

f. It can be seen that an appreciable difference exists between d-c plate resistance and a-c plate resistance, the latter being approximately one-half of the former. This is, in general, true for all types of vacuum tubes. Furthermore, as figure 33 shows, the a-c resistance also is related to the plate voltage, *decreasing* as plate voltage is *increased*, and *increasing* as plate voltage is *decreased.* The *exact value of a-c resistance depends on the point of operation se-*

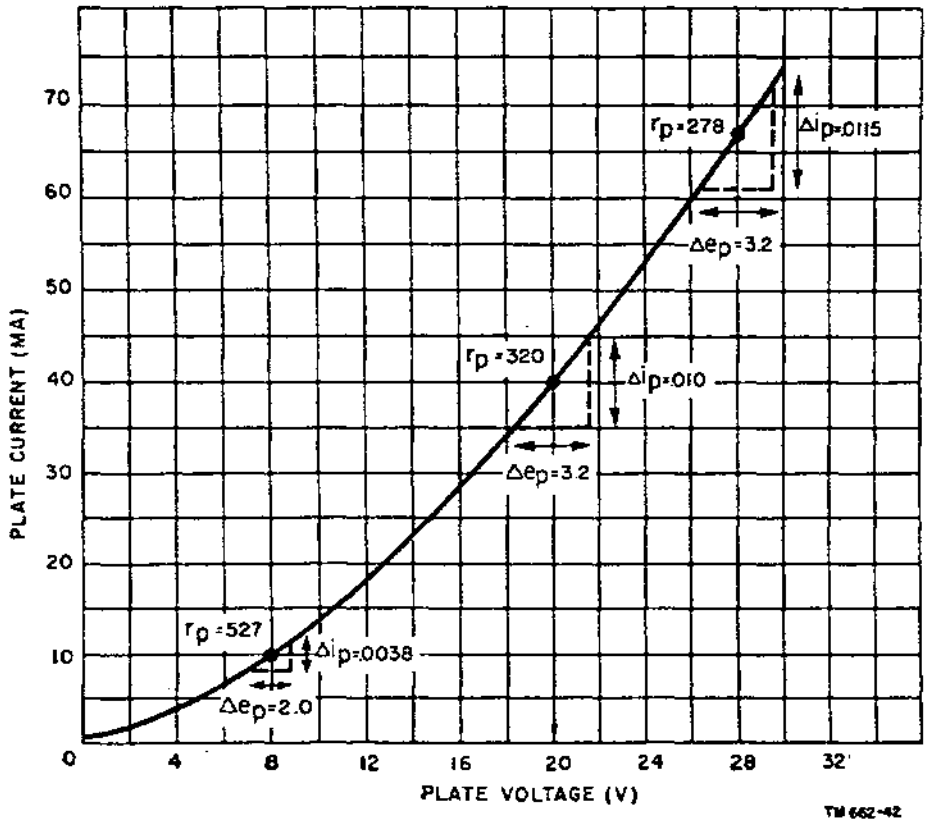


Figure 33. Plate-current plate-voltage characteristic which can be used to determine the a-c plate resistance of a diode.

lected on the characteristic curve. Consequently, if the point of operation is at a plate voltage of 20 volts, the a-c plate resistance is greater than when the operating point chosen corresponds to a mean plate voltage of 28 volts.

26. Static and Dynamic Diode Characteristics

a. The discussion of diodes thus far has been for static conditions and not for actual operating conditions. For a diode, or any tube, to be able to perform its normal function, its external circuit must contain a *load.* It is through this load that the diode current flows outside the tube, and the *voltage drop developed across this load then represents the output of the tube.* With such a load, represented by a resistance R_L (fig. 34), the operating characteristic of the tube is changed materially. The plate-current plate-voltage curve is altered noticeably, and it represents the *dynamic* characteristic rather than the *static* characteristic which applies when there is no load.

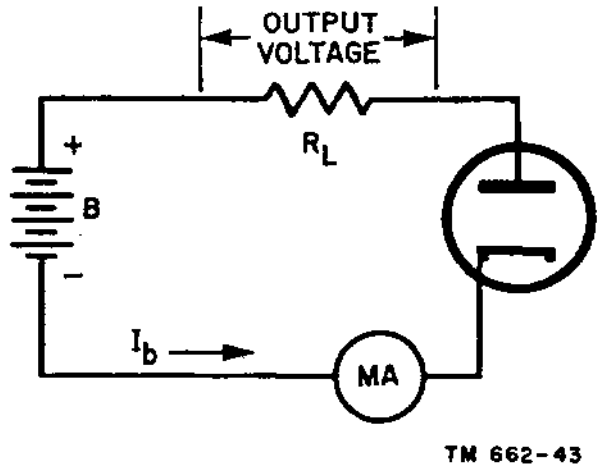


Figure 34. Adding a load resistor, R_L, to a diode circuit to obtain an output voltage.

b. With no load in the circuit, or when R_L equals 0, the resistance in the circuit is the resistance of the tube; also, the small resistances of the battery and meter are present, but these can be neglected. But when an external resistance, the *load resistance,* is added (fig. 34), the total opposition to plate-current flow includes that of the tube itself and also that of the load. When the load resistance is many times the value of the internal resistance of the tube, the tube resistance offers only a negligible percentage of the opposition to plate-current flow. Consequently, if the external load resistance maintains its value regardless of the amount of current flowing through it, the plate-current plate-voltage characteristic of the system is changed from a curved line into a substantially straight line.

c. These various conditions can be noted on a separate graph (fig. 35). The dashed line represents the static characteristic—that is, when there is no load resistance. Solid line 1 illustrates the voltage-current relationship when the load resistance is 1,000 ohms. This line possesses some curvature, but it is considerably less than that of the static line. Solid line 2 is obtained with a load resistance of 10,000 ohms. This line is almost straight; some curvature appears in the region of low plate voltage where the internal resistance of the tube is highest. A line representing a value of 100,000 ohms is so straight throughout its length that it lies too close to the horizontal axis, and it cannot be drawn clearly on the graph. Therefore, the higher the load resistor value, the straighter is the dynamic curve, and the lower is the amount of plate current flowing in the circuit. This is not a disadvantage, provided the load resistance is maintained within reasonable limits.

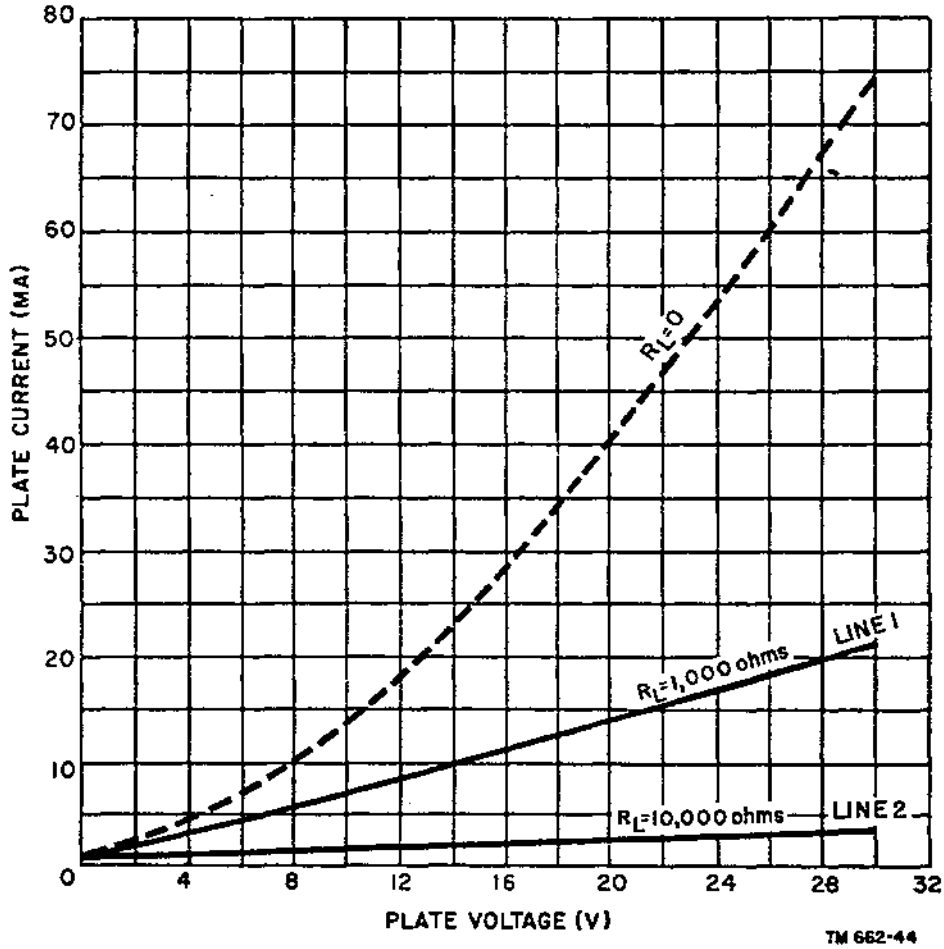


Figure 35. Plate-current plate-voltage characteristic curves of diode having different load values.

d. A linear dynamic characteristic is desired for the diode, principally because it assures proportionality between applied plate voltage and output current. This affords freedom from distortion in many circuits that use the diode, although, in other applications, distortion is of secondary importance. The most important consideration is the use of a load; a *load* is necessary if a diode is to be of practical use.

27. Uses

a. Since current flow in the diode is unidirectional, one of its most prominent uses is as a rectifier or converter of alternating current into direct current. In figure 36, an alternating voltage is used as the plate voltage. During the positive alternations of the input voltage, the plate is positive relative to the cathode, and plate current i_p flows through the tube and load resistance R_L. The current develops a voltage drop across the load. At every instant the output voltage (in volts) is:

$$e \text{ output} = (i_p \times R_L)$$

where R_L is the load resistance in ohms

i_p is the instantaneous current in amperes.

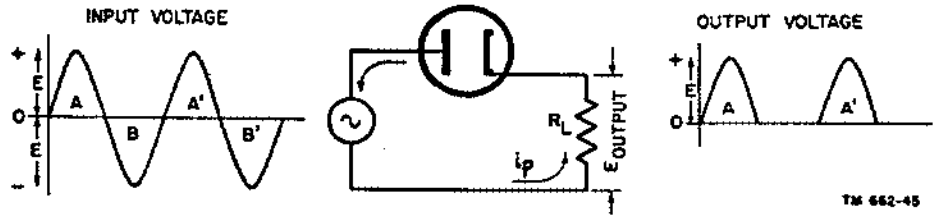


Figure 36. Diagram illustrating unidirectional current flow in diode.

c. Concerning the action in figure 36, it can be seen that the changes in current amplitude follow the instantaneous changes in applied plate voltage. This becomes evident when the input plate-voltage alternations, A and A', are compared with the output voltage pulsations, A and A'. These pulsations have the same shape as the two positive alternations of the applied voltage. The absence of conduction in the tube during the two negative alternations, B and B', of the input voltage is caused by the diode plate being negative with relation to the cathode during these periods. If the input voltage has a frequency of 60 cps (cycles per second), the output current pulses will occur 60 times per second, each lasting for a period equal to one-half of each input cycle.

d. Both single- and dual-section diodes have many other uses, developed later in this manual. All of these depend on the principle of unilateral conduction through the tube.

28. Types

High-vacuum diode tubes are available in various types (fig. 37), differing principally in physical dimensions and shape. They differ internally as well but not in the fundamental arrangement of the electrodes. The physical dimensions are related to the magnitudes of voltages applied to the plate and the currents flowing through the tube during operation. Tubes used in circuits which handle signal voltages of relatively low values are known as signal diodes. Another general category is that of power diodes or vacuum-tube rectifiers which handle high values of voltage and current. Eac of these types is intended for special application and they are not interchangeable. Signal diodes are restricted to signal circuits. Power diodes generally are used in power circuits, except where certain signal systems entail relatively high voltages, and circuit operation demands an action similar to rectification.

29. Electron Transit Time

a. The time required for an electron to traverse the distance from the cathode to the plate of a diode, or other kinds of electron tubes, is

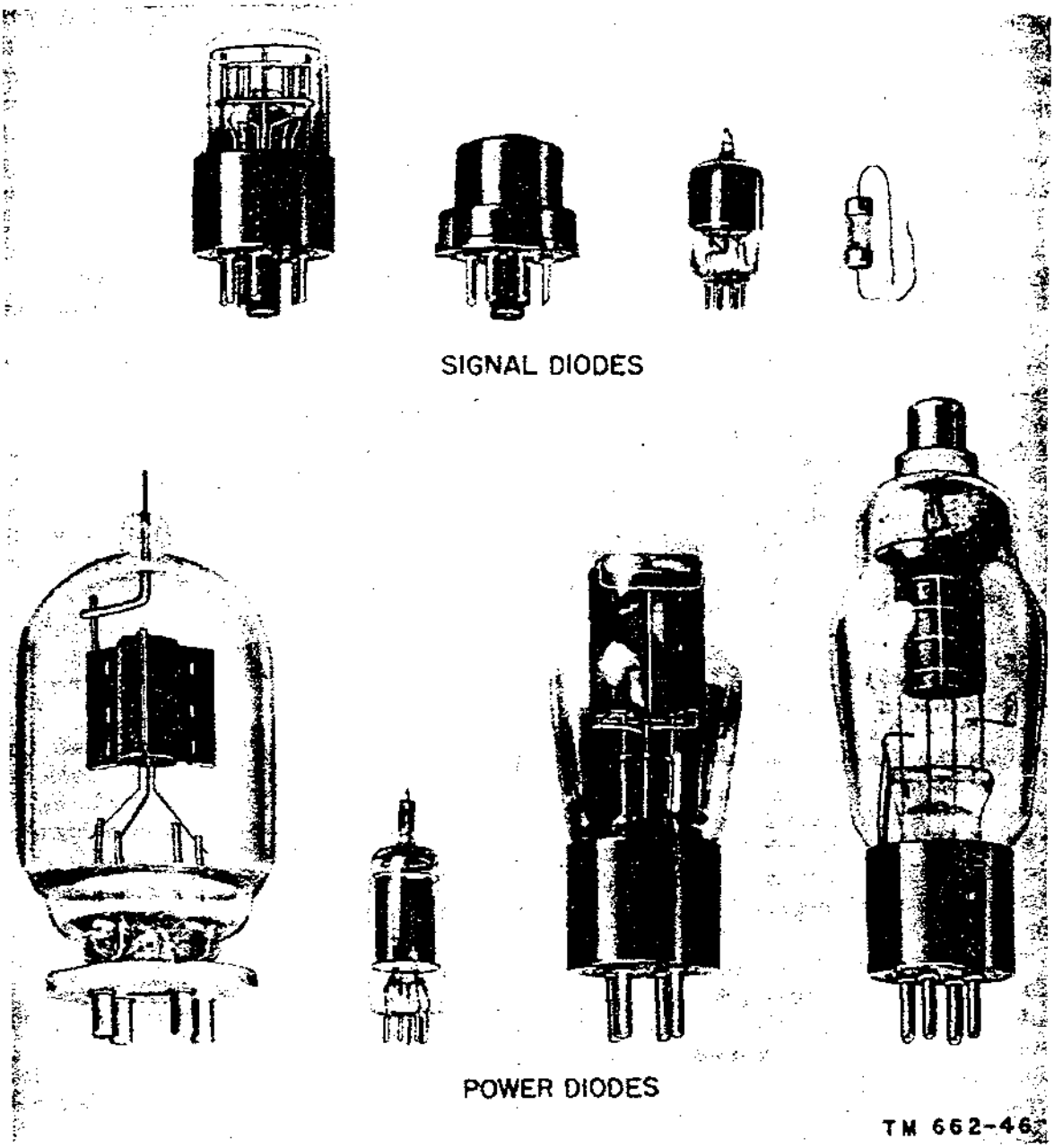


Figure 37. Various types of high-vacuum diodes.

called *electron transit time.* At operating frequencies below 200 mc, transit time introduces no particular problems. Under such conditions, the movement of the electron conforms with the changes in instantaneous amplitude and polarity of the plate voltage. This can be described more broadly by saying that the output plate current conforms with instantaneous changes in tube electrode voltages.

b. As the frequency of the electrode voltage rises, above 200 mc, for example, the transit time becomes an appreciable part of the cycle. The elapsed time for the completion of 1 cycle of a 200-mc voltage is one two-hundredth of a

microsecond. The positive alternation of such a voltage is completed in one four-hundredth of a microsecond, or .0025 usec. For example, suppose that the applied plate voltage and the physical arrangement of the electrodes are such that .005 usec is required for the electron to travel from the cathode to the plate. Then if a 200-mc signal is applied to the plate, the electron undergoes a change while traveling to the plate because the polarity of the plate voltage has reversed from that which existed a moment earlier.

c. A *lag* of this kind cannot be tolerated because it interferes with the operation of the system. Therefore, diodes (and other electron tubes) are designed specially for use at very high frequencies. As a rule, these design differences are found in the physical spacing between electrodes and in the value of the applied voltages. Moreover, such tubes bear special designations indicating their suitability for very-high- and ultra-high-frequency applications.

30. Summary

a. The diode is a two-electrode tube containing an emitter of electrons and a collector of electrons. The emitter is known as the filament or cathode. In modern usage, the term *cathode* is used to indicate either type. Cathodes are of two types, directly heated and indirectly heated. The collector is commonly known as the *plate* and sometimes is referred to as the anode.

b. The flow of electrons in a diode constitutes the plate current. Plate-current flow in a diode is unidirectional, and the tube is, therefore, a unilateral conductor. This underlies the use of the diode as a rectifier.

c. The direction of plate-current flow is identical to that of electron flow, that is, from negative to positive.

d. An electron in an electrostatic field moves toward the positive limit of the field, its velocity per unit time being a function of the difference of potential existing between the limits of the field.

e. The important features of a vacuum tube can be obtained from its characteristic curves. A number of curves drawn on the same graph are known as a family of curves.

g. One of the effects interfering with maximum plate-current flow in a tube is that resulting from the presence of the space charge. The space charge is caused by an accumulation of electrons in the immediate vicinity of the cathode. In this position, it tends to repel electrons back to the cathode and prevents them from flowing toward the plate.

h. The state of equilibrium in which the maximum density of the space charge for every fixed temperature of the cathode is reached is known as *emission saturation*, or the *saturation point.* The value of plate current flowing at that time is referred to as the *saturation current.*

i. Two types of resistance are present in a diode, the d-c plate resistance and the a-c plate resistance. This also is true of other types of tubes.

j. The phenomenon of electron transit time is not a factor of importance in medium- and high-frequency operation of vacuum tubes, but it is of very special concern in ultra-high-frequency operation.

k. The principal uses of the diode are as a rectifier and as a detector.

31. Review Questions

a. Describe the construction of a diode and draw its schematic.

b. By what other names are these identified: the emitter of electrons and the collector of electrons in a tube?

c. Describe two principal methods for heating electron emitters. Which is more commonly used?

d. Name the two types of rectifiers using diodes. What feature of diode operation makes possible its use as a rectifier?

e. What is a duo-diode and how does its construction differ from that of a regular diode? Illustrate schematically.

f. When an electron moves in an electrostatic field between two charged surfaces, what de-

termines (a) its direction of travel, (b) its velocity of motion?

g. In a vacuum tube, why do electrons flow from the cathode to the plate but not in the reverse direction?

h. In what respect does a diode act like a valve when comparing it to the flow of plate current in a diode?

i. What is the *space charge* in a tube and how does it affect the operation of the tube? Is it desirable?

j. Name four factors that control plate-current flow in the diode.

k. Identify the two electrostatic fields present in a diode.

l. How does the plate current of a tube vary as the plate voltage is increased? Show this by a graph. Can the plate current be increased indefinitely by increase of plate voltage?

m. What is a positive ion?

n. What is meant by the *equilibrium* of the space charge?

o. Explain the terms emission saturation, saturation point, saturation current.

p. What is the effect of a load resistance upon plate-current flow and upon the dynamic curve?

q. What are some kinds of important information that can be obtained from characteristic curves?

r. What relationship is brought out in a plate-current plate-voltage characteristic curve?

s. In what sense do characteristic curves *operate in both directions?*

t. Explain and illustrate the terms *linear and nonlinear.*

u. What are the two types of resistances present in a diode?

v. What general information is contained in a family of characteristic curves?

w. What is the difference between the static and dynamic characteristics of a vacuum tube?

x. Name some types of diodes.

y. What action of the electron is referred to by the term *electron transit time?*

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

EXTRACT

Paragraphs 32—44

United States Government Printing Office
Washington: 1952

GO 22448

CHAPTER 4

TRIODES

32. Control Grid

a. GENERAL.

(1) The invention of the *triode*, or three-element tube, was one of the most important steps in modern electronics. Up to 1907, the diode was the only electron tube used in the primitive wireless communication systems of that time. In that year, DeForest disclosed his *third element*, an electrode which was added to the diode and so formed the triode. Not only did it modify the diode, but it opened a new era in communication facilities. DeForest's third element made present-day radio communication in all its forms a practical reality.

(2) The emitter and the plate as used in the diode appear also in the triode. They retain their functions as a source of electrons and a collector of electrons, respectively. In the space between them, and located nearer to the emitter, is placed the third element, commonly called the *control grid*.

b. PHYSICAL CONSTRUCTION OF TRIODE.

(1) Figure 38, illustrating the organization of the cathode, control-grid, and plate electrodes of the triode, is an example of the oval-shaped form of grid, and shows how the grid surrounds the emitter on all sides. The plate electrode is seen enveloping the control grid. Other examples of triode construction exist, but they do not differ greatly from this.

(2) The dimensions and the shape of the electrodes used in triodes, as well as the physical spacing between the electrodes, differ in accordance with the intended uses of the tubes. Since these are related to such details as the values of plate voltage and plate current, the elements of triodes used in transmitters generally are larger than those of tubes used in receivers.

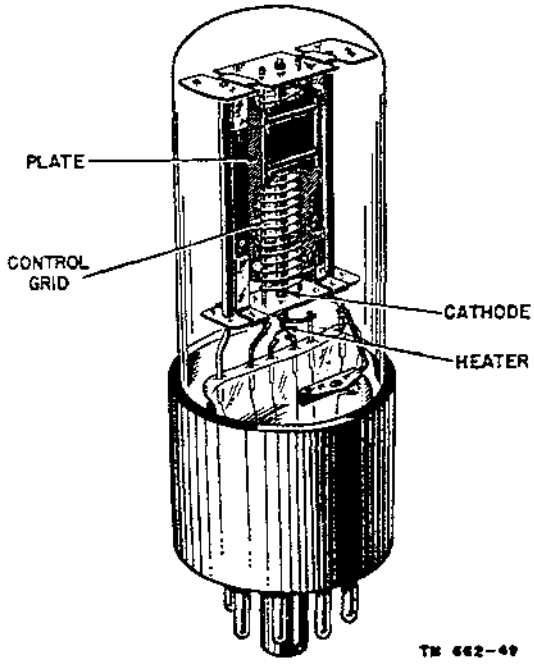


Figure 38. Construction of triode, showing cathode, control-grid, and plate arrangement.

(3) The internal structure of the triode seldom is completely visible through the envelope. When the envelope is made of metal, the reason is obvious. When the envelope is made of glass, the view of the inside usually is obscured because of the opaque coating formed by the *getter* when the tube is *flashed*, that is, heated to a high temperature. The getter is a substance that is placed within the envelope for

the express purpose of absorbing any gases that may be liberated from the electrodes during initial operation. This keeps the vacuum created in the tube as high as possible. Magnesium is widely used as a getter, but other materials, such as barium, zirconium, and phosphorous, also can be used.

(4) The opaque deposit formed by the getter appears as a thin film on the lower half of the inside surface of the glass housing. The top usually remains transparent, and some visual inspection of the electrodes inside is therefore possible. This is the usual means for determining whether the electron emitter is incandescent. In the larger transmitting tubes, the getter coating usually does not obscure the metal parts inside the tube.

c. CONSTRUCTION OF CONTROL GRID.

(1) In appearance, the control grid is a ladderlike structure of metal. In most cases, it has a helical form, consisting of a number of turns of fine wire wound in the grooves of two upright supporting metal structures (fig. 39).

(2) The metals used for grids are usually molybdenum, nichrome, iron, nickel, tungsten, tantalum, and alloys of iron and nickel. The different physical sizes of the control grid, as well as the spaces between the turns that form the electrode, reflect different designs of triodes. The emitters and the plates are similar to those used in diodes.

d. SYMBOL FOR CONTROL GRID. When shown symbolically, the control grid (fig. 40) appears between the symbols used for the emitter and the plate, as either a zig-zag line, in A, or a

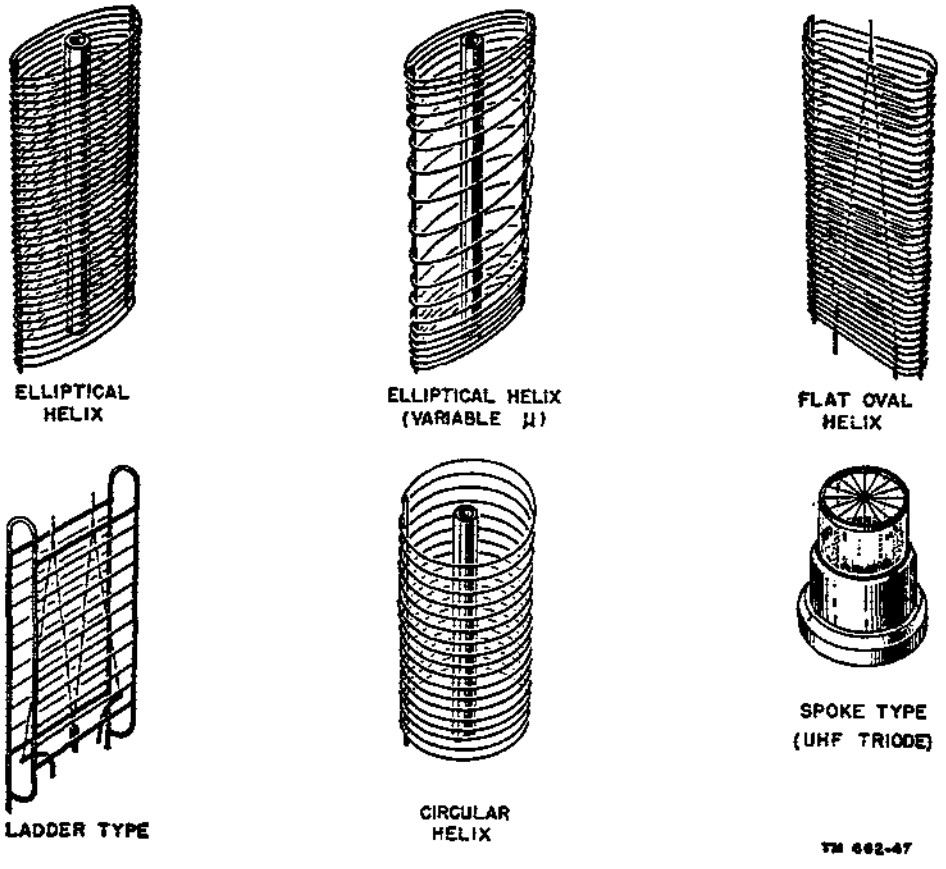


Figure 39. Typical control-grid assemblies.

dashed line, as in B. The symbol using the dashed line is the standard form in Signal Corps schematics. The letter identification of the control grid in the triode electron tube is the capital letter G, although in some instances the letters CG are used.

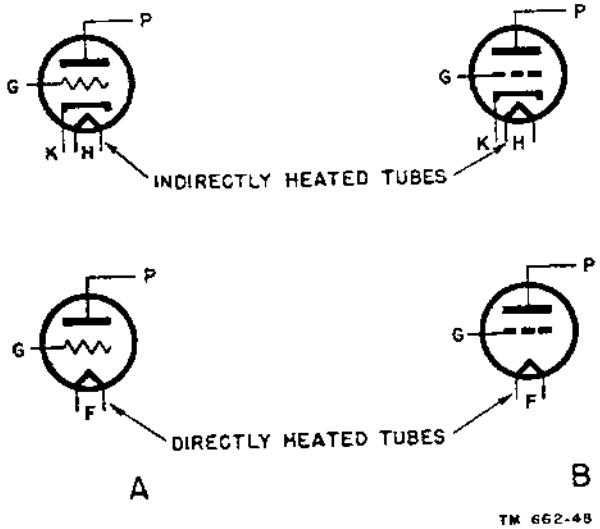


Figure 40. Symbols for directly and indirectly heated triodes.

e. PURPOSE OF CONTROL GRID.

(1) Briefly, the purpose of the control grid is to govern the movement of electrons between the cathode and the plate, thereby controlling the instantaneous plate current flowing through the tube. As previously mentioned, the voltage applied to the plate determines the amount of electrons attracted to it. What, then, is the electrical difference between the triode and the diode?

(2) Essentially, the diode can change alternating current to pulsating direct current. When an a-c voltage is applied to the plate, the instantaneous value of plate current is a direct function of the instantaneous polarity of the applied plate voltage, assuming, of course, that the emitter temperature remains constant. In the triode, a voltage on the control grid can vary the plate current when the voltage applied to the plate of the triode is held constant.

(3) The polarity and amplitude changes in voltage applied to the diode plate result in a unidirectional flow of pulsating plate current. In the case of the triode, the voltage applied to the plate of the tube is a d-c voltage obtained from a constant voltage source, but the action of the control grid can, nevertheless, cause variations in the amplitude of the plate current. The statement just made concerning the situation at the plate of a tube is a very important and fundamental point of distinction between the diode and the triode.

(4) The control grid can stop the flow of electrons to the plate. This is the same as saying that the plate current can be cut off despite the presence of a d-c voltage on the plate of the tube.

(5) The positive plate voltage can be as high as 5,000 volts, and, with proper negative grid bias, the control grid can overcome completely the influence of the high voltage. Consequently, it can be said that the control grid controls the current in the plate circuit. This control is external. If current and voltage in a system are representative of electrical energy in that system, then the control grid in the triode is an independent agency affording control of the amount of electrical energy present at any instant in the plate circuit.

(6) The ability of the control grid to govern the flow of plate current is used in many ways. Stopping all plate current is an example of an extreme condition. In addition, the control grid can decrease or increase the plate current instantaneously, even though the positive voltage applied to the plate is constant. It can also create current conditions in the plate circuit which are equivalent to changes in the plate voltage. Finally, the control grid can be made ineffective so that it does not control the plate current at all.

(7) It is natural if the preceding statements lead to the impression that the grid in the triode behaves like a valve by controlling the instantaneous value of plate current. It is common to refer

to the control grid in this manner, although the term valve is not fully descriptive of all the uses of a grid. Nevertheless, the valve action is very important, for it is the basis of the many functions of a triode, especially its ability to deliver a stronger signal than it receives. This process is called *amplification*. It should be pointed out, however, that vacuum tubes actually do not amplify power. In fact, the grid actually controls the flow of power from the plate power supply.

f. SUPPLY VOLTAGES OF A TRIODE.

(1) To operate properly, every triode requires a means of heating the emitter. This is accomplished by a *heater* or *filament* voltage. The voltage source sometimes is referred to as an A-battery (fig. 41). It is connected to the filament in the directly and the indirectly heated triodes, shown in A and B respectively. This d-c voltage commonly is known as the *heater supply* or the *A-supply*. As a matter of simplicity, the discussion of the triode will be carried on using the indirectly heated triode as the basis.

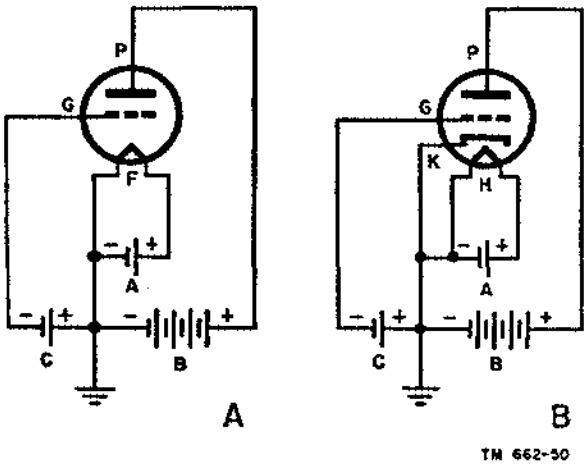


Figure 41. D-c supply voltages of directly and indirectly heated triodes.

(2) Since the plate in the triode functions as an attractor of electrons, it is understandable that a source of *positive* plate voltage (in reference to cathode) is required. This source is the B-battery (fig. 41), also called the *B-supply* or *plate-voltage supply*. Electrically, it is connected between the plate and the electron emitter, with the positive terminal of the supply joining the plate of the tube. The junction between the negative terminals of the A- and B-batteries usually is grounded in standard practice.

(3) The third electrode of the triode is the control grid. Discussion of the movement of electrons in the diode (ch. 3) has made clear that control of plate current by means of an added electrode is accomplished by setting up an additional electrostatic field. A field of this kind results from the application of a voltage difference between the grid and another point. Therefore, by all sound reasoning, the control grid should be subject to a voltage.

(4) A third source of voltage, generally assigned the letter C, is connected between the control grid and the emitter (fig. 41). The polarity connections of the C-battery make the control grid negative with relation to the electron emitter. This is standard practice for reasons which will be explained shortly. For the moment, it should not be considered in that light, but viewed rather as a voltage connected between the control grid and the emitter. The reason for this approach is the manner in which the action of the control grid will be analyzed. It will be examined under these conditions: positive relative to the emitter, negative relative to the emitter, and zero potential relative to the emitter.

(5) The circuits in figure 41 are of fundamental triode systems suitable for study. Each diagram shows the voltage sources applied to the electrodes of this type of tube. However, all systems do not use batteries as the source of operating voltages. The voltages can be secured from other sources. The heater or filament voltage, marked A, can be obtained from an a-c trans-

former, or from rotating machinery such as a d-c generator. The plate-voltage source, labeled B, can be a d-c generator, or it can be a device designed for the purpose of furnishing d-c voltages from a variety of primary power sources. Such a device is known as a *power supply.*

(6) The grid-voltage supply, labeled C, also can be secured from a power supply or from special circuits associated with the tube itself, which will be described later.

(7) The circuits of figure 41 warrant additional comments. Previous statements concerning the thermionic type of diode associated that tube with one fixed operating voltage, the heater or filament voltage. The voltage applied to the plate was shown as dc only, for the purpose of explaining the operating characteristics. In rectifier applications, this voltage is alternating and is representative of the a-c power that is being applied to the tube for conversion to d-c power.

(8) In the triode (fig. 41), the situation is different. Here, the three electrodes receive fixed d-c operating voltages. These determine the manner in which the tube functions and performs the duties assigned to it. As long as an electron tube is used as a triode, it bears direct association with a value of heater or filament voltage, a plate voltage, and a control-grid voltage. Sometimes these are referred to as the *operating potentials.*

(9) Another very important detail concerning the operating voltages of the triode (as well as of other vacuum tubes containing three or more electrodes) is the reference point of the applied electrode voltages. In almost all cases it is the cathode, or the common junction point of the voltage sources, shown connected to ground in figure 41 because this is a standard practice in almost all cases. To measure the plate voltage, a voltmeter would be connected between the plate electrode and the common ground junction. The same is true for the control-grid voltage: the measurement would be made between the control grid and the common ground point.

33. Input, Output, and Cathode Circuits of Triode

a. GENERAL. The application of the triode and other vacuum tubes which contain three or more electrodes is founded upon a division of the electrode circuits into three systems (fig. 42): the *input, output,* and *cathode* circuits. A shows an indirectly heated and B a directly heated triode.

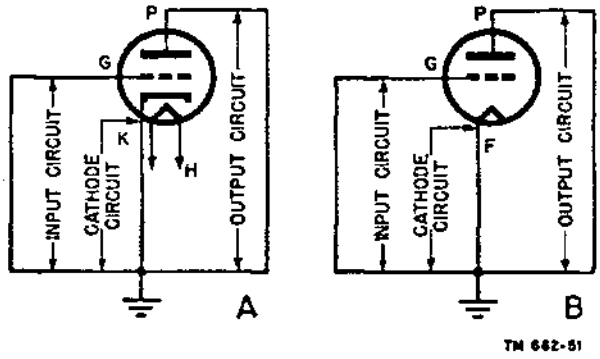


Figure 42. Input, output, and cathode circuits of indirectly and directly heated triodes.

b. DISTINCTION BETWEEN CIRCUITS.

(1) The *input* circuit encompasses all circuit elements between the control-grid electrode as one boundary and the grounded common voltage reference point as the other circuit boundary. The *output* circuit includes all component parts between the plate electrode and the common voltage reference point. Finally, the cathode circuit includes all the elements in the system between the emitter proper and the common voltage reference point.

(2) The circuit division is based on the voltages applied to the electrodes even though the different voltage sources have been omitted. It also is related to the paths of signal currents that flow in the tube circuits. It is too early in this treatment to speak about these,

but they will appear again later in this manual.

34. Electrostatic Field in Triode

a. SPACE-CHARGE CONDITIONS.

(1) An imaginary view of the electrodes of a triode without any voltages applied to the control grid and the plate, but with the cathode at emitting temperature, is shown in figure 43. The letter K designates the electron-emitting cathode, G is the control grid, and P is the plate. Each grid wire is represented as a small circle. Electrically, these circles are connected. The separation between the grid wires is ample to allow electrons to travel between the wires toward the plate. The space charge is shown by the tiny dots between the cathode and the control grid. The greatest space-charge density is seen to exist nearest the cathode (par. 17). Note the absence of electrons in the space between the control grid and the plate. Some of the emitted electrons have sufficient velocity after emission to advance to the plate, but these are so few in number as to be unimportant in the discussion. Consequently, it is completely satisfactory to show the space between the control grid and the plate devoid of electrons. It is only when current is passing through the tube that electrons are present in this space.

(2) In figure 43, note the physical locations of the control grid and the plate relative to the space charge. The control grid is very much closer to the space charge than the plate is. In fact, the entire space charge is assumed to be located between the cathode and the control grid. The actual physical separation between the electrodes of an electron tube is a matter of individual tube design. This aspect of electron-tube construction is unimportant in this discussion, although it can be stated that these dimensions usually are in small fractions of an inch, except in the very large transmitting tubes, in which the tube electrodes are farther apart.

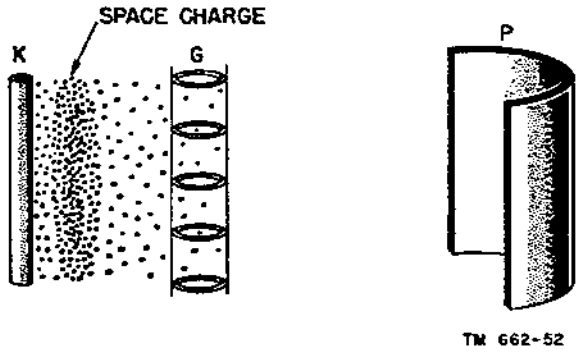


Figure 43. Imaginary view of electrodes in a triode.

b. BEHAVIOR OF CONTROL GRID.

(1) In figure 44, the cathode is assumed to be emitting an adequate supply of electrons. The B battery applies 100 volts to the plate, making it positive relative to the cathode by that amount. The control grid is at zero potential relative to the cathode, as shown. Mention of zero voltage difference between two points does not imply an open circuit; it means that both points are at the same potential or that there is no difference of potential between them.

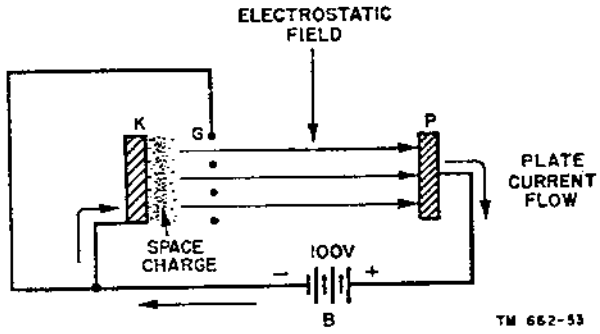


Figure 44. Electron flow in triode with control grid at cathode potential.

(2) The triode is a thermionically heated electron tube; therefore, a space charge exists in the neighborhood of the cathode, between that electrode and the control grid. This cloud of electrons is inherent in every tube of

this kind, regardless of the number of electrodes.

c. CREATION OF ELECTROSTATIC FIELD. The electrostatic fields created by this organization of electrodes and the voltage relationships are symbolized by the arrows in figure 44. With zero voltage applied to the grid, the latter has no electrostatic field of its own. The positive voltage applied to the plate causes an electrostatic field to exist between the cathode and the plate (par. 17).

d. DIRECTION OF ELECTROSTATIC FIELD. The direction of the field is such as to pull electrons toward the plate. They advance to it through the spaces between the control-grid wires. The amount of plate current flowing through the tube and around the external plate circuit back into the cathode is a function of the voltage applied to the plate, or space-charge limiting that takes place. For the sake of clarity and because the plate voltage has been stated as 100 volts, a plate current of 20 ma is assumed. This value is purely illustrative, and is not intended to imply any plate-current plate-voltage relationships for triodes in general.

e. CONTRIBUTION OF CONTROL GRID. So far, the action of the triode is not much different from that of the diode. The control grid, at cathode potential, contributes very little, if anything, to the behavior of the triode. It is important, however, to consider the *grid current* which flows in the control-grid cathode circuit because of what it means during application of control-grid voltages and its association with the operating voltage conditions at the control-grid electrode.

f. GRID CURRENT.

(1) The spaces between the control-grid wires allow free movements of electrons to the plate (fig. 44). The control grid is, however, a physical structure; therefore, the grid wires can block the passage of some of the electrons advancing toward the plate. There is no force that tends to make the grid wires attract electrons to it, but since it is in the path of the plate-current electrons, some charges will attach themselves to the control-grid wires. This results in a small amount of *grid current* flow in the control-grid cathode circuit.

(2) Slight as it is, this grid current is, nevertheless, undesirable for several reasons. All of them relate to the ultimate performance of the tube. Some of them are associated with the proper performance of the devices which are used with the tube. Since it is too early in the discussion of the triode to explain each of these effects, they will be explained later. However, it can be said that the usual triode operating conditions are such as to prevent the attraction of electrons to the control grid, and therefore, the flow of grid current.

35. Negative Voltage on Control Grid

a. GENERAL. Another set of operating voltage conditions for the triode (fig. 45) is identical with that shown in figure 44, except for the insertion of a 1-volt C-battery which makes the control grid *negative* relative to the cathode by 1 volt.

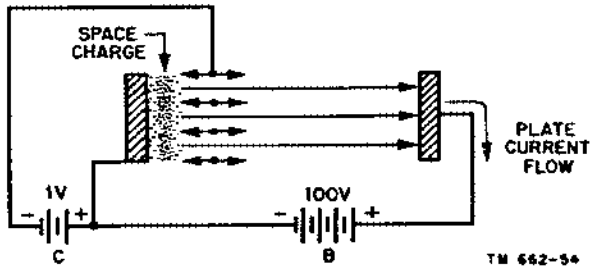


Figure 45. Electron flow in triode with control grid negative in relation to cathode.

b. ELECTROSTATIC FIELD. The voltages applied to the plate and the control grid produce two separate electrostatic fields (fig. 45). The positively charged plate has a field which attracts electrons toward the plate. The negatively charged control grid has a field which repels electrons toward the cathode.

c. PATH OF ELECTRON.

(1) On the side of the control grid which faces the space charge, the negatively charged grid acts to repel electrons back into the space charge, thereby reducing the number of electrons

which advance to the plate. This tends to increase the density of the space charge, which causes a greater number of the emitted electrons to be repelled back into the cathode in order to maintain equilibrium of the space charge. Immediately, the situation implies a reduction in plate current; however, this is not the complete story.

(2) On the side of the control grid which faces the plate, the direction of the electrostatic field is toward the plate. Consequently, once an electron has traveled into the area between the control grid and the plate, all the forces acting on it attract it toward the plate. Even though this effect takes place, it is not too important in relation to the negative grid.

d. EFFECT OF ELECTROSTATIC FIELD. Figure 45 shows that the lines of force in the plate field penetrate the space between the grid wires and act on the space charge, tending to pull electrons to the plate. At the same time, the lines of force on the cathode side of the control grid tend to prevent electrons from advancing to the plate. The movement of electrons through the openings of the grid to the plate is controlled by the force that predominates.

e. EFFECT OF CIRCUIT VOLTAGES.

(1) It would seem from the simple relation between numbers that the negative 1-volt potential on the control grid and the positive 100-volt potential on the plate would create fields of such relative intensity as to enable the plate field to overwhelm the grid field completely. This does not occur, because the control grid is much closer to the space charge than the plate is. Therefore, a low voltage applied to the control grid can exert as much, or more, influence on the space-charge electrons as a very much higher voltage applied to the plate.

(2) Making the control grid 1 volt negative with relation to the cathode can offset as much as plus 10, 20, or even 50 volts applied to the plate. In some types of triodes the effect may be less, and in still other types can be greater. For the purpose of comparing figures 44 and 45, the —1-volt grid bias in figure 45 reduces the original plate current by 10 ma, making it 10 ma instead of the 20 ma flowing with 0 grid voltage in figure 44.

(3) In some tubes, —1 volt applied to the control grid can stop the movement of electrons completely, thus cutting off the plate current. Such a condition is known as *cut-off*, and the amount of negative grid voltage necessary to cause this state is known as the *cut-off voltage*. In some instances, cut-off is not reached until perhaps —10 volts, —20 volts, or more are applied to the control grid. The exact value is determined by the design of the tube.

36. Positive Voltage on Grid

What happens if the voltage applied to the control grid is positive, thereby making the control grid positive relative to the emitter? This is not the most frequently used operating condition, but it warrants an explanation because it is found in some applications.

a. ELECTROSTATIC FIELD. The change in polarity of the control-grid voltage modifies the direction of the electrostatic field between grid and cathode (fig. 46). This field tends to pull electrons out of the space charge and accelerate them toward the plate; because of the positive voltage on the control grid, great numbers of electrons pass through the grid openings as they advance toward the plate. The field produced by the positive voltage on the plate also is pulling electrons toward the plate; consequently, the positively charged control grid can be described as aiding the plate voltage, thereby increasing the plate current. It is assumed in the example cited that the plate current is increased 10 ma, so that the current is now 30 ma instead of the 20 ma indicated in figure 44.

b. PATH OF ELECTRONS. Many of the electrons attracted from the space charge by the positive control grid are intercepted in their advance to the plate by the grid wires. This results in grid current which is much larger in value than when the control grid was held at 0 voltage.

c. EFFECT OF PLATE VOLTAGE. The extent to which a positive voltage applied to the control

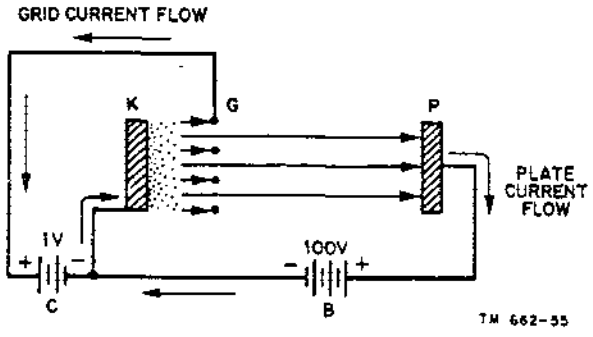


Figure 46. Electron flow in triode with control grid positive in relation to cathode.

grid offsets the space charge and increases plate current is determined by the design of the particular triode. In some tubes, a grid voltage change of a few volts may have the same effect on plate current as changing the plate voltage by 10, 20, or oven 50 volts. In other instances it may be more or less.

d. PLATE-GRID RELATIONSHIPS. The exact quantitative relationship between changes in the control-grid voltage and changes in the plate voltage for equal changes in plate current is dependent upon the individual tube type design. This is a very important *constant* of every triode, and, for that matter, of every type of electron tube which uses more than two electrodes. It determines the suitability of a tube to meet a functional need.

37. Summary of Control-grid Action

a. PICTORIAL SUMMARY. A pictorial summary of the control-grid action associated with figures 44 through 46 is shown in figure 47. Positive and negative polarities and values of control-grid voltage are pictured over a period of time in curves A and C. An imaginary switch mechanism in the grid circuit provides 0, +1, and —1 volts at the control grid. The 1-volt positive and negative limits are arbitrary. The graphs of these voltage variations may assume the shape of a sine or a square wave, as shown in curves A and C. For purposes of easiest correlation with the resultant plate-current changes (curves B and D), each interval of grid-voltage level and polarity is labeled. Corresponding labels appear on the plate-current curve.

b. CONCLUSIONS. The specific values of plate current shown in curves B and D are also arbitrary, but for the sake of simplicity are made to conform with the values stated above during the description of the grid-voltage conditions. Correlating the plate-current changes in curve B with the grid-voltage changes in curve A shows that—

(1) When the grid voltage is held at zero potential (curve A, periods 1 to 2, 5 to 6, and 9 to 10), the plate current is constant at a value determined only by the attractive force of the positive plate voltage. This current is represented in curve B, periods 1′ to 2′, 5′ to 6′, and 9′ to 10′.

(2) A change in grid voltage from 0 to a positive 1 volt (curve A, 2 to 3) results in an increase in the plate current (curve B, 2′ to 3′).

(3) A change in grid voltage from 0 to a negative 1 volt (6 to 7) causes a decrease in plate current (6′ to 7′).

(4) Where the grid voltage assumes a steady positive 1-volt value for a period of time (3 to 4), the plate current also remains constant (3′ to 4′) at the new value created by the positive voltage on the grid.

(5) Where the grid voltage assumes a steady negative 1-volt value for a period of time (7 to 8), the plate current also remains constant (7′ to 8′) at the new value created by the negative voltage on the grid.

(6) The direction of change in grid voltage has a definite relationship to the direction of change in plate current. As the grid voltage changes in the positive direction from 0 (2 to 3), the plate current increases (2′ to 3′). As the grid becomes less positive (4 to 5), the plate current decreases (4′ to 5′). As the grid voltage increases in the negative direction (6 to 7), the plate current decreases (6′ to 7′). As the grid becomes less negative (8 to 9), the plate current increases (8′ to 9′).

(7) The changes in plate current occur in step with the changes in grid voltage.

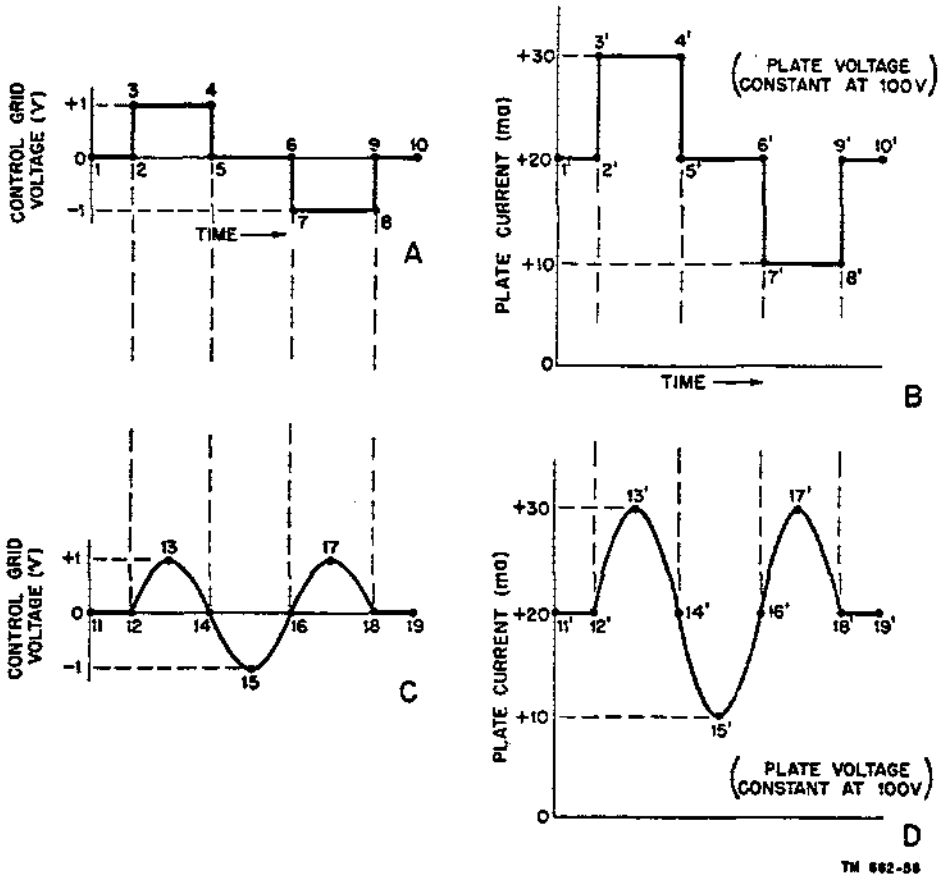


Figure 47. Curves showing relationships between grid voltage and plate current in triode.

The maximum and minimum points of one occur at the same instant as the maximum and minimum of the other. This is commonly referred to as an *in-phase* condition.

38. Additional Characteristics

a. UNIDIRECTIONAL FLOW. Curves A and B warrant some additional discussion. The changes in grid voltage in each direction represent a change in polarity relative to a 0 reference voltage. However, the changes in plate current are not changes in polarity, but rather represent variations above and below a reference value of current. The reference value of plate current in curve B is +20 ma, which corresponds to the grid reference volt of 0 volt in curve A. Curve B shows that even when the plate current is at its lowest value (7′ to 8′), it still has a value greater than 0 (+10 ma). The polarity of the plate current always remains positive. No other value is possible because of the unidirectional current flow in the tube. The voltage applied to the grid makes the unidirectional plate current greater or smaller in value, in conformance with the instantaneous amplitude and polarity changes of the grid voltage.

b. GRID-PLATE RELATIONSHIPS. Another pertinent detail is that the plate-current grid-voltage relationship is not dependent on sudden changes in grid voltage. The grid voltage can change slowly or very rapidly and the plate current will vary accordingly. This is symbolized by the sine-wave voltages shown in curves C and D. In general, it can be said that the change in plate current usually has the same shape as the change in control-grid voltage. This is not a rigid rule; it is subject to numerous modifications as dictated by the way in which the tube is used. Subsequent explanations will make this point clear.

c. TRIODE OUTPUT. The final point to be made about a varying plate current in the plate circuit of a triode is that it can be looked upon as a steady direct current to which is added an alternating-current component. This results in a current which has a unidirectional flow but which varies in value above and below a steady reference value. In curve C, 11 to 12 and 18 to 19 are the steady (0 grid voltage) reference values. In curve D, 11′ to 12′ and 18′ to 19′ show the steady reference value of corresponding plate current, 20 ma. The a-c voltage applied to the control grid (curve C, points 12 through 18) momentarily increases the plate current to a maximum (curve D, points 13′ and 17′), 30 ma, and momentarily decreases it to a minimum (point 15′), 10 ma. This plate current can be described as a direct current of 20 ma with an a-c component equal to 10 ma peak.

39. Bias, Signal Voltage, and Plate Current

a. GRID-CURRENT EFFECTS. It has been stated that a value of positive voltage on the control grid results in the presence of grid current between the control grid and the cathode through the system external to the tube. This condition cannot be avoided, because the grid wires intercept electrons which are advancing toward the grid on their way to the plate. The positively charged grid attracts electrons into itself. Disregarding for the moment any applications which permit grid current, the presence of grid current normally is undesirable. It represents the consumption of power and other unwanted effects.

b. BIAS AND SIGNAL VOLTAGES. The signal voltage normally applied to an electron-tube control grid is alternating in character; at least, it is a voltage which varies in amplitude and perhaps in polarity relative to the cathode. During the time that it is negative with relation to the cathode, freedom from grid current is obvious, but when it is positive, grid current is present unless some means are provided to keep the control grid at a negative potential during the positive portion of the input signal. The purpose of the negative control-grid *bias* is to establish this operating condition. Bias may be defined as the d-c voltage between the grid and the cathode. It is represented by battery C in figure 48. The total voltage existing between grid and cathode is the signal voltage plus the bias voltage.

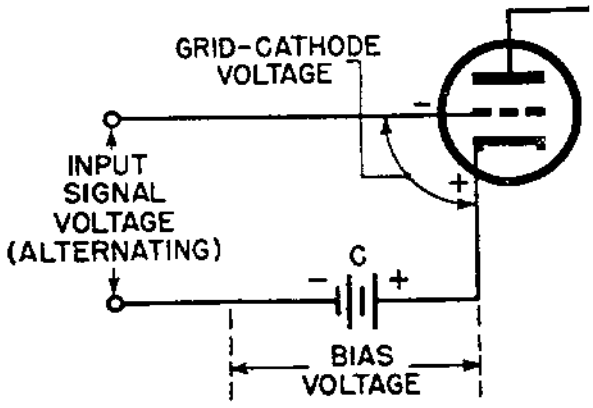


Figure 48. Bias and signal voltages of a triode.

c. BIAS-SIGNAL REPRESENTATIONS.

(1) The association between the signal and the grid bias is illustrated in figure 49. Curve A represents an input a-c signal of 5 volts peak. It varies between +5 and —5 volts. In order to keep the control grid negative during the entire positive alternation of the input signal, the grid bias must equal, if not exceed, the peak value of the signal. Therefore, the control-grid bias is arbitrarily set at —6 volts, as in curve B. Since the grid is negative with relation to the 0-voltage reference level, it is shown *below* the reference voltage line.

(2) The resultant of the signal and control-grid bias voltages at the control grid, instant by instant, is shown as curve C in the same illustration. Curve C is the addition of curves A and B. The fixed bias voltage sets up the initial voltage relationship between the control grid and the cathode. This is the no-signal condition as in curve B. It is represented by 1 to 2 and 8 to 9 in curve A and 1′ to 2′ and 8′ to 9′ in curve C. The times from 1 to 2 and 8 to 9 in curve A represent the period

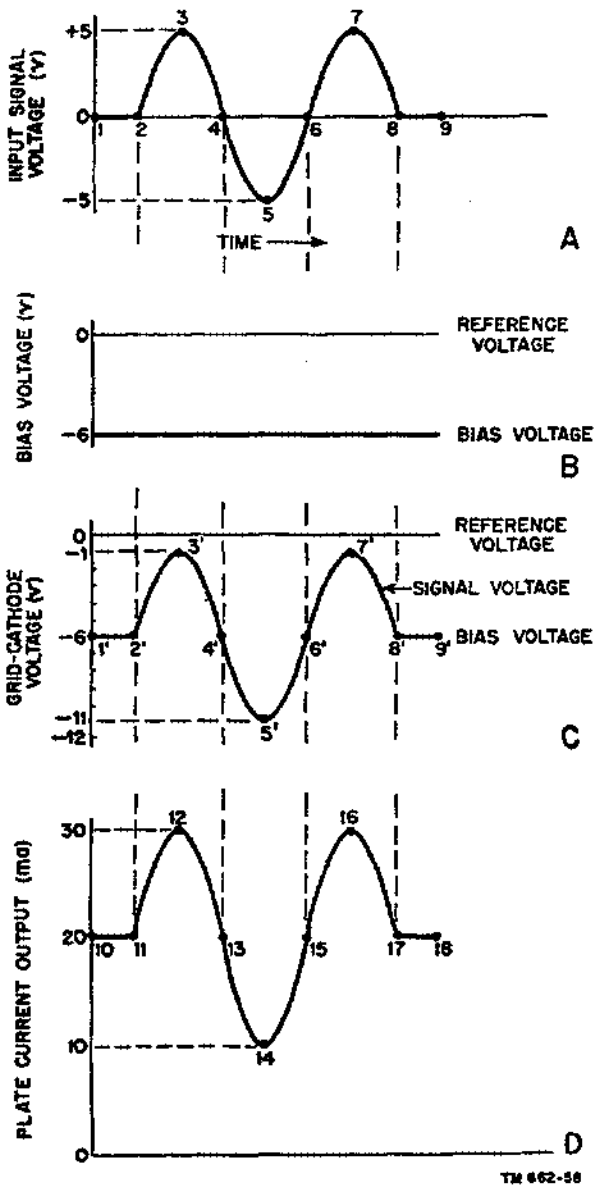


Figure 49. Waveshapes illustrating bias, signal voltage, and plate current.

of 0 signal voltage, during which time the full —6 volts of grid bias is active on the control grid, as shown in times 1′ to 2′ and 8′ to 9′ in curve C.

(3) As the signal voltage starts rising in the positive direction (from 2 to 3), it bucks the fixed negative bias, and the control grid becomes less and less negative until, at the peak of the positive alternation of the signal voltage (point 3), the control grid is 1 volt negative with relation to the cathode, as shown by 3′ in curve C. As the signal voltage decreases in positive amplitude (from 3 to 4 in curve A), more and more of the bias voltage becomes predominant until point 4 is reached, which again corresponds to 0 signal voltage. The control grid again becomes 6 volts negative with relation to the cathode, as shown by point 4′ on curve C. Examining the action during the positive half-cycle of the applied signal voltage, points 2′ to 4′ in curve C, it is evident that a 5-volt change in signal voltage in the positive direction has taken place at the control grid, but the grid electrode remains negative throughout the half-cycle.

(4) During the negative alternation of the signal voltage (points 4 to 6), the signal and the fixed negative bias voltages add. The result is a change in voltage at the grid from —6 volts (4′ in curve C), to a maximum negative voltage of —11 volts (5′) and then a return to —6 volts (6′) again. The control grid remains negative with relation to the cathode by an amount equal to the sum of the instantaneous signal voltage and the fixed grid bias.

d. PLATE-CURRENT REPRESENTATIONS. The plate current varies in accordance with the instantaneous resultant of the signal and fixed bias voltages, as in curve D. Without a signal input, but with the bias applied, the plate current is of constant amplitude (10 to 11 and 17 to 18) at 20 ma. When the signal voltage is applied, the plate current increases and decreases above the no-signal value.

e. GENERAL.

(1) It is interesting to note that curves C and D show changes in voltage and current, respectively; they are in step above and below the no-signal values. Each of these curves represents a combination of d-c and a-c components.

(2) The grid bias may be referred to as being increased. This means that it

is a higher value of bias, making the control grid more negative with reference to cathode. When reference is made to a reduction of bias, it means a lower value of voltage, or one which makes the control grid less negative.

40. Characteristic Curves

a. GENERAL. The relationships between the different voltages applied to the triode and the effects they have on the plate current are very important. As in the case of the diode, they are illustrated by means of *characteristic* curves, except that the curves which display the behavior of triodes are more numerous and present more varied information.

b. TRIODE CONSTANTS. The suitability of a triode or any other kind of electron tube for an application is determined by the *constants* of the tube. An understanding of the meaning of triode constants and the manner in which they are determined is pertinent to proper use of the tube. Accordingly, subsequent paragraphs are devoted to the subject.

41. Triode Circuit Notations

a. GENERAL NOTATIONS. Before explaining triode characteristics, it is necessary to refer briefly to the several triode circuit notations that will appear in the discussion. The electrodes of vacuum tubes are referred to by their common names, such as control grid, plate, filament, and cathode. Voltages and currents related to these electrodes also are treated in the same way: for example, plate voltage, plate-supply voltage, plate current, and control-grid voltage.

b. LETTER NOTATIONS. Such long names can prove unwieldy in text or in illustrations, especially when they need frequent repetition. To overcome this difficulty, it is common practice to assign letter *notations* to indicate certain voltages and currents under different operating conditions. A complete list of these appears in the appendix to this manual. Figure 50 illustrates a simple triode circuit bearing several circuit voltage and current notations which are used often. Only immediately pertinent notations are shown:

(1) E_{bb} = the plate-supply voltage, or the amount of B voltage.

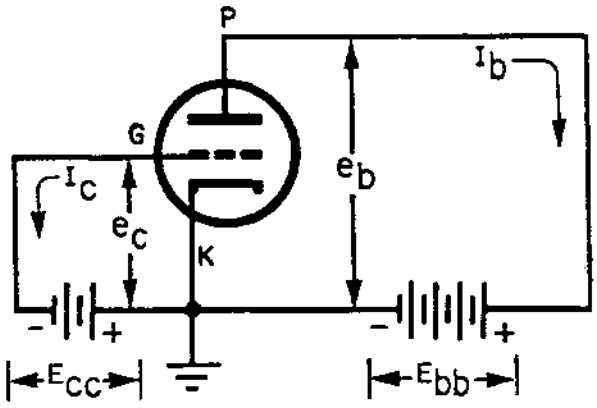
(2) e_b = the instantaneous total plate voltage. (In fig. 50, E_{bb} equals e_b because there is no plate load.)

(3) I_b = the total steady plate current.

(4) E_{cc} = the control-grid supply voltage, the C voltage, or the grid-bias voltage.

(5) e_c = the instantaneous total grid voltage. (In fig. 50, E_{cc} equals e_c because there is no input signal.)

(6) I_c = the total steady grid current.



TM 662-59

Figure 50. Triode circuit bearing several voltage and current notations.

c. OTHER NOTATIONS. Attention is called to the use of capital letters E and I for *steady* values of voltage and current and to the use of small e and i for instantaneous values of voltage and current. The conditions depicted in figure 50 do not involve instantaneous values of current, and therefore, the small letter i is absent. The subscript letters c and b associate the voltage or the current with the tube electrodes. Only a few circuit notations are introduced at this time. More will follow as the subject unfolds in this manual.

42. Static Plate-current Grid-voltage Characteristics

a. GENERAL. In view of the electrode organization of the triode, three basic factors control the plate current: the emitter temperature, the control-grid voltage, and the plate voltage. The first of these can be disregarded, for, unless

otherwise stated, it is general procedure in all vacuum-tube operation to assume that the emitter is being operated at the required temperature. Accordingly, it is necessary merely to stipulate the emitter temperature in terms of heater or filament voltage or current upon whatever tube characteristic is being illustrated.

b. VARIABLE FACTORS. This, then, leaves the control-grid voltage and the plate voltage as the two variable factors (causes) which contribute to variations in plate current (the effect). To treat two variables simultaneously with no constants is impossible; consequently, each of these is considered separately. The effect on the plate current of a change in grid voltage is considered first; this characteristic is known as the plate-current grid-voltage characteristic. Plate voltage must be applied to the triode plate; therefore, the characteristic is developed with a known and stipulated plate voltage. If it is desired, individual plate-current grid-voltage characteristics can be developed for different values of plate voltage. Both kinds of characteristic graphs are treated in this manual.

c. CONSTRUCTION OF CHARACTERISTIC.

(1) The construction of a static plate-current grid-voltage characteristic is a relatively simple procedure. Different values of grid voltage, starting at 0 and advancing first in the positive direction and then in the negative direction (or the reverse) are applied. The plate current flowing at each increment of grid-voltage change is plotted on a suitable graph. If the changes are in steps of 1 volt, the final characteristic shows the plot of plate current over a range of grid voltages from zero to some negative limit, say —6 volts, and from zero to some positive limit, say +6 volts (in 1-volt steps). The graph is laid out in the way described in paragraph 26. The known variable is considered to be the *cause* and is marked off along the abscissa or horizontal axis. The unknown variable, or *effect*, is marked off on the ordinate or vertical axis (A of fig. 51). This is the static plate-current grid-voltage characteristic for a tungsten filament emitter triode.

(2) The use of the word *static* in connection with the characteristic means that the curve represents tube behavior under no-load conditions. The voltages applied to the electrodes are determined solely by the voltage sources, such as E_{cc} and E_{bb} in figures 50 and B of 51.

(3) The vertical dividing line projecting upward from the 0-voltage point on the grid-voltage axis divides the plate current curve into two parts. The portion left of the 0-voltage dividing line shows the plate-current curve when the grid voltage is negative. The portion to the right of the 0-voltage line shows the plate-current curve when the grid voltage is positive. In all cases, the value of plate current is indicated by the scale on the ordinate, or the vertical axis.

d. EXPLANATION OF CHARACTERISTIC.

(1) The circuit capable of producing the data contained in this graph is illustrated in B of figure 51. Grid-voltage source E_{cc} is so arranged that a variable voltage, either negative or positive, can be tapped to the control grid. An arbitrary choice limits the grid-voltage changes to a maximum of about 7 volts in a positive or negative direction. Appropriate voltmeters VM indicate the applied grid and plate voltages. The ammeter, AM, shows the plate current flowing in the system for each increment of grid voltage.

(2) Referring to the characteristic, it is seen that with the plate voltage fixed at a constant value, plate current starts flowing at about —6 volts on the grid. As the control grid is made less negative by adjusting voltage supply E_{cc}, the plate current increases, but in a nonlinear manner. From approximately —2.75 volts up to about —.75 volt, the plate-current rise is in direct proportion to the reduction in grid voltage. This is the *linear* part of the characteristic, or the straight portion.

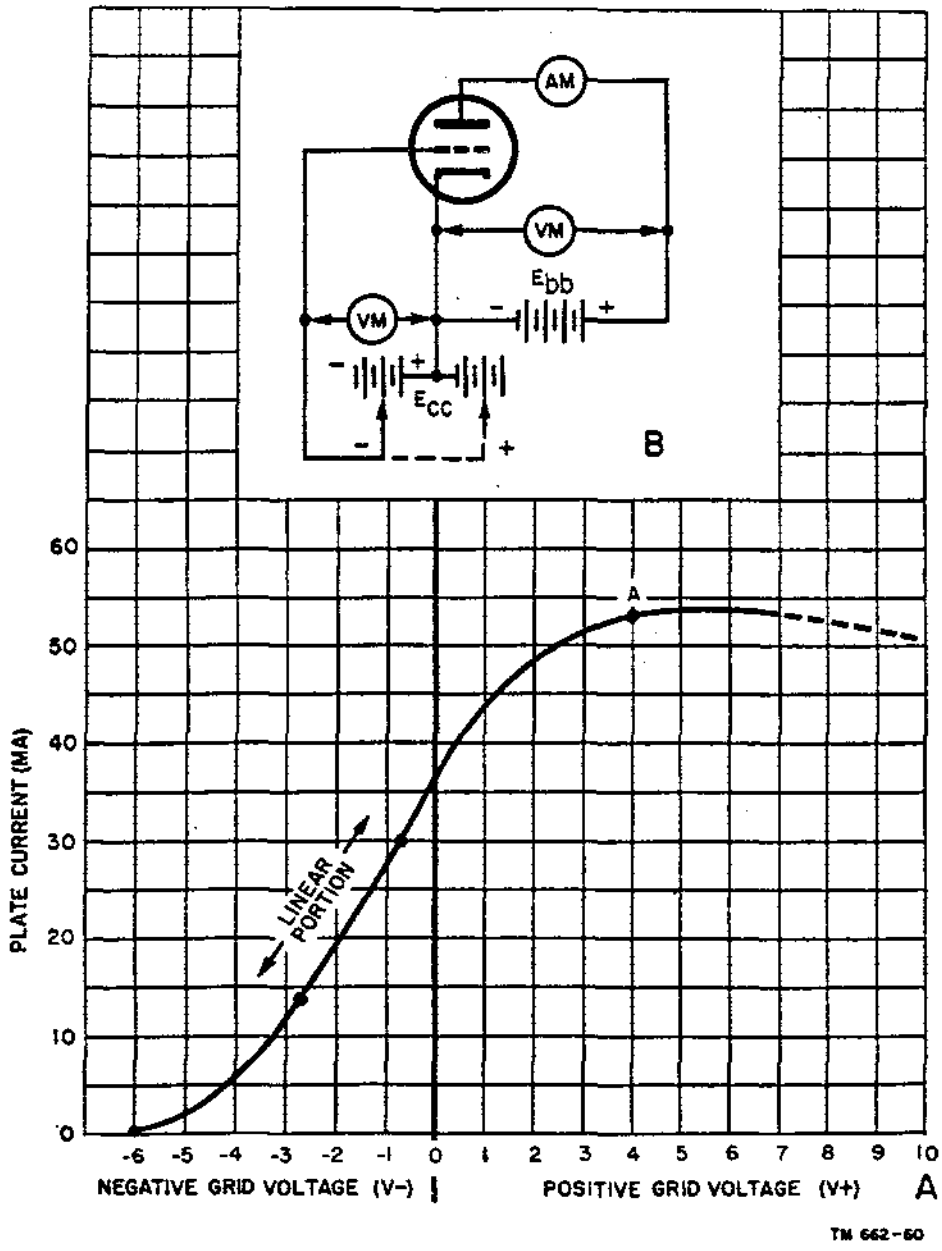


Figure 51. Plate-current grid-voltage characteristic curve for a typical triode circuit.

As the control-grid voltage approaches 0 and passes into the positive grid-voltage region, the plate current continues to increase, but again in nonlinear manner.

e. CONCLUSIONS. Several pertinent conclusions can be drawn from this plate-current grid-voltage characteristic. As the grid is made more and more positive, the plate current continues to increase until the rise in grid voltage produces no further increase in plate current. At this value of positive grid voltage, the plate-current curve flattens off. This occurs at approximately point A, which usually is identified as the plate-current saturation point. It is the value of plate current beyond which no further increase in plate current occurs as the grid is made more positive.

f. OTHER FACTORS.

(1) Plate-current saturation is a peculiarity of tungsten filament tubes. For any one emitter temperature, there occurs a fixed maximum emission. Plate saturation corresponds to that condition when, with the fixed amount of emission from the tungsten filament, all the emitted electrons divide between the grid current and the plate current, and making the control grid more positive does not increase the plate current.

(2) Even this does not remain static. If the control grid is made sufficiently positive, it will *reduce* the plate current, as shown by the dotted-line curve beyond point A in figure 51. The fall in plate current is due to the emission of *secondary* electrons from the plate while under bombardment by the high-velocity electrons which comprise the plate current. These secondary electrons are attracted by the highly positive grid. In a sense, electrons are moving in two directions across the area between the highly positive grid and the positively charged plate. The current flow to the plate consists of those electrons coming from the cathode which pass through the spaces between the grid wires. The higher the positive voltage on the grid, the greater the velocity of these electrons, but fewer reach the plate because of the greater attracting force present at the grid wires. The other flow is from the plate to the grid inside the tube, these being the secondary electrons knocked out of the plate by the electrons which advance from the space charge to the plate. The net result is an over-all reduction of plate current.

g. USING OXIDE-COATED EMITTER..

(1) The plate-current grid-voltage characteristic for an oxide-coated emitter triode, curve ABC (fig. 52), warrants several comments. The absence of plate-current saturation is noted immediately. The oxide-coated emitter is so profuse in electron output that even with a highly positive grid there remains an ample supply of electrons to cause plate current to flow. This means a continually increasing plate current as the grid is made more positive. Raising the plate voltage would have the same effect; that is, the plate current would continue to rise. In the figure, the plate voltage is held constant at 100 volts.

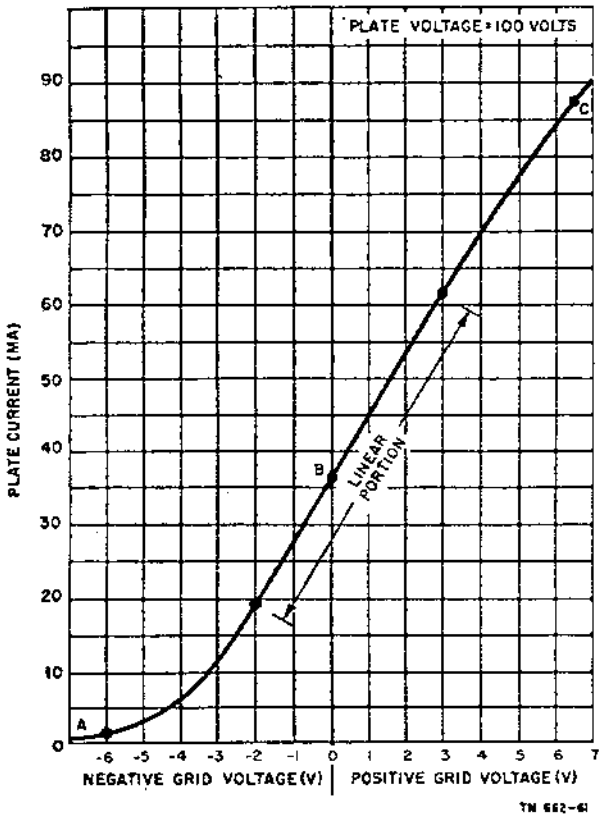


Figure 52. Plate-current grid-voltage characteristic curve for triode using oxide-coated emitter.

(2) The shape of the characteristic in the negative grid-voltage region is very much like that for the tungsten emitter triode. This is to be expected because the fundamental relationships between the tube electrodes are determined only in part by the type of emitter. The grid voltage required for a constant plate current is seen to be much higher than for the tungsten

emitter triode. This is incidental because the specific value of grid voltage required to level off the plate current is determined by the characteristics of the tube. The important point is that every triode is subject to a constant plate current and finally cut off if the grid is made sufficiently negative.

h. GRID-CURRENT EFFECTS. The plate-current grid-voltage characteristic of the oxide-coated emitter in figure 52 is seen to be substantially linear in the positive grid-voltage zone. This does not imply that normal use of the tube is with grid current flowing. In some cases it is used in this manner, but in the majority of instances the control grid is held at some negative d-c value. Whenever the grid is positive, power is consumed in the grid circuit, since the grid then draws current. If the source of grid voltage can compensate for the consumption of power, all well and good, but this type of operation is a special case, and not the usual. As will be seen later, grid-current flow is unusual in receiving system tubes, but it is common in tubes used in transmitters.

i. SUMMARY.

(1) The previous descriptions of tube behavior have the one purpose of making clear the manner in which the various supply voltages acting on the space charge are translated into numbers to form a graph.

(2) Different voltages applied to the plate modify the shape of the characteristic curves shown in figures 51 and 52. All tube characteristic curves have linear and nonlinear portions, although not necessarily to the same degree. The cut-off voltages differ, but every plate-current curve displays the effect because it is inherent in every vacuum tube. Finally, the meaning of plate-current change versus grid-voltage change has been illustrated in a way which leads to further explanations of tube behavior when plate voltages are increased or decreased.

43. Grid Family of Characteristic Curves

a. GENERAL. A single plate-current grid-voltage characteristic curve furnishes important information, but it is limited. A number of such curves shown on the same scale for different values of plate voltage give much more information concerning the effects of the different grid voltages on the plate current. Such curves plotted on a single graph comprise a *family* of characteristic curves, in this instance, the grid family. Another name used is *static transfer characteristics.*

b. GRID FAMILY. As a rule, the grid family or static transfer characteristics do not involve the positive region of grid voltage. This is so because for most triode applications the grid is not driven positive. A direct comparison between figures 51, 52, and 53 is, therefore, not possible. The first two represent arbitrary operating conditions and values, whereas figure 53 treats a specific tube, the 6J5. The circuit used to develop the data shown in figure 53 is similar to that in B of figure 51, except that the plate voltage, E_{bb}, is variable over a substantial range.

c. OBTAINING GRID FAMILY OF CURVES. Each curve in figure 53 is identified by a specific value of applied plate voltage, and is, therefore, the resultant of the stated plate voltage and changes in grid voltage. The curve is formed by noting the plate current as the control-grid voltage is increased in the negative direction, beginning at 0 voltage. These points are joined and form a curve. The —18-volt bias limit is set by that range of plate voltages (100 to 300 volts) considered within the performance capabilities of the tube.

d. ANALYSIS OF CURVES.

(1) A number of facts immediately become evident. There is a close similarity between the general contours of the characteristic curves. Each has a linear and a nonlinear part. Moreover, each plate-current curve has a cut-off point (on the X-axis), and it is seen that as the plate voltage increases, the value of negative bias required to cut off the plate current also increases. For example, —6.5 volts causes cut-off when the plate voltage is 100 volts, whereas —12.6 volts is required when the plate voltage is 200

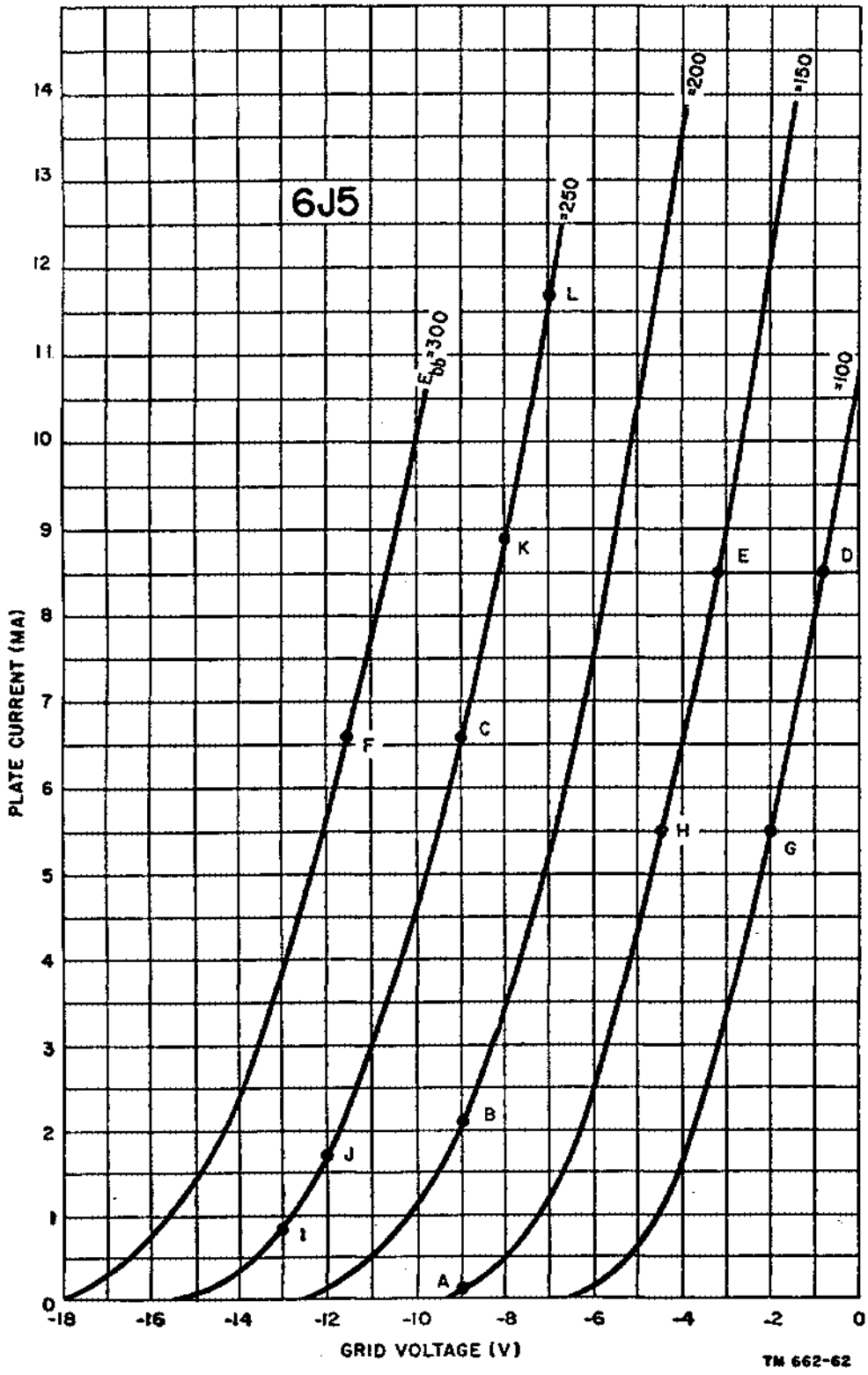


Figure 53. Grid family of characteristic curves for 6J5 triode.

volts and —15.5 volts cuts off the plate current when the plate voltage is 250 volts.

(2) The grid family also discloses an increase in plate current for an increase in plate voltage when the bias voltage is held constant. For example, a —9-volt bias (point A) results in .1 ma plate current with 150 volts applied to the plate, a 2.1-ma (point B) plate current at 200 volts on the plate, and a 6.55 ma (point C) plate current with 250 volts applied to the plate.

(3) The amount of grid voltage required to offset a change in plate current when the plate voltage is changed can be determined from the grid family. This can be restated by saying that these curves indicate the required increase or decrease in bias in order that the plate current be held constant when the plate voltage is changed. For example, point D on the 100-volt plate-voltage curve corresponds to 8.5 ma with a negative bias of .8 volt. If the plate voltage is increased to 150 volts, and the plate current must be held at 8.5 ma (point E), the grid bias must be increased to —3.2 volts. This indicates that an increase of 50 volts in plate voltage is offset by an increase of 3.2 minus .8 or 2.4 volts bias. In similar fashion, points C and F, each representing 50-volt increases in plate voltage, require an increase of 2.5 volts in negative grid voltage in order that the charge in plate voltage be offset and the plate current remain constant at 6.55 ma.

(4) The curves work in the reverse direction as well. They indicate the change in plate voltage required to offset a change in negative grid bias for constant plate currents. For example, assume a starting point G, representing 100 volts on the plate and —2 volts on the grid, and 5.5 ma of plate current. If the bias is increased to —4.4 volts, what is the new value of plate voltage which will result in the same plate current of 5.5 ma? A vertical projection from the —4.4-volt bias point intersects the 5.5-ma current projection along the 150-volt plate-voltage curve (point H). This leads to the conclusion that a 4.4 minus 2 or 2.4-volt increase in negative grid bias demands a 50-volt increase in plate voltage in order to hold the plate current constant.

(5) Still more information is available from the grid family. This is seen between points I-J and K-L along the 250-volt characteristic. It shows that the change in plate current corresponding to a fixed change in bias voltage (grid voltage) is a function of the *operating region* on the plate-current curve. Consider a 1-volt change, between —12 and —13 volts (I-J) on the curve of E_{bb} = 250 volts. The plate-current change is .84 ma, going from .86 to 1.7 ma. The same 1-volt grid-voltage change higher upon the curve from —7 to —8 volts (K-L) results in a change of 2.8 ma, going from 11.7 to 8.9 ma.

(6) Examination of the plate-current curve where E_{bb} = 300 volts discloses even a greater change in plate current for 1-volt changes in grid voltage. The opposite is true if E_{bb} = 200 volts. This can be seen if the points, —7 to —8 volts, are plotted on the plate-current curve of E_{bb} = 200 volts. A change of 1.8 ma takes place, from 3.5 to 5.3 ma. This value is 1 volt less than the previous value obtained at 2.8 ma when E_{bb} was equal to 250 volts. This leads to the generalization that the higher the plate voltage applied to any one type of electron tube, the greater is the change in plate current for a given change in grid voltage.

e. OPERATING POINT. The *operating point* along the plate-current grid-voltage curve deserves some emphasis. This term should be understood thoroughly because it is repeated frequently later. It is important to recognize the association between the location of the operating region on the curve and the manner in which it determines the amount of change in

plate current per unit change in grid voltage. Proportional changes occur only over the *linear* (straight) parts of the curve. The greatest change in plate current per unit change in grid voltage occurs along the straight, rather than the curved part of the characteristic.

44. Static Plate-current Plate-voltage Characteristics

a. OBTAINING PLATE FAMILY OF CURVES. Figure 54 shows a *static plate family* of characteristic curves obtained by using the same circuit as that used in B of figure 51. In this family of characteristics, the grid voltage is varied in steps of 2 volts, and the plate-current measurements are made over a continuously variable range of plate voltages. For example, with the grid voltage at 0, or $E_{cc} = 0$, the plate voltage is varied from 0 to approximately 135 volts, and the plate current can be noted for this range. Joining the individual plate-current points results in the curve $E_{cc} = 0$. The grid voltage then is increased to —2 volts, or $E_{cc} = -2$, and the plate current again is noted for a new range of plate voltage, starting with that value which is just offset by the grid voltage—in this case 35 volts—up to about 170 volts. These new points of plate current are joined and they form the second curve ($E_{cc} = -2$). In every instance, the plate-current range shown for a particular fixed grid voltage starts at the point along the plate-voltage axis where the grid voltage causes plate-current cut-off. Each curve is drawn over a range of about 135 volts change in plate voltage.

b. USES OF CURVES. In general, the grid family and the plate family furnish the same information, except in somewhat different forms. Whereas the grid family displays the plate cur-

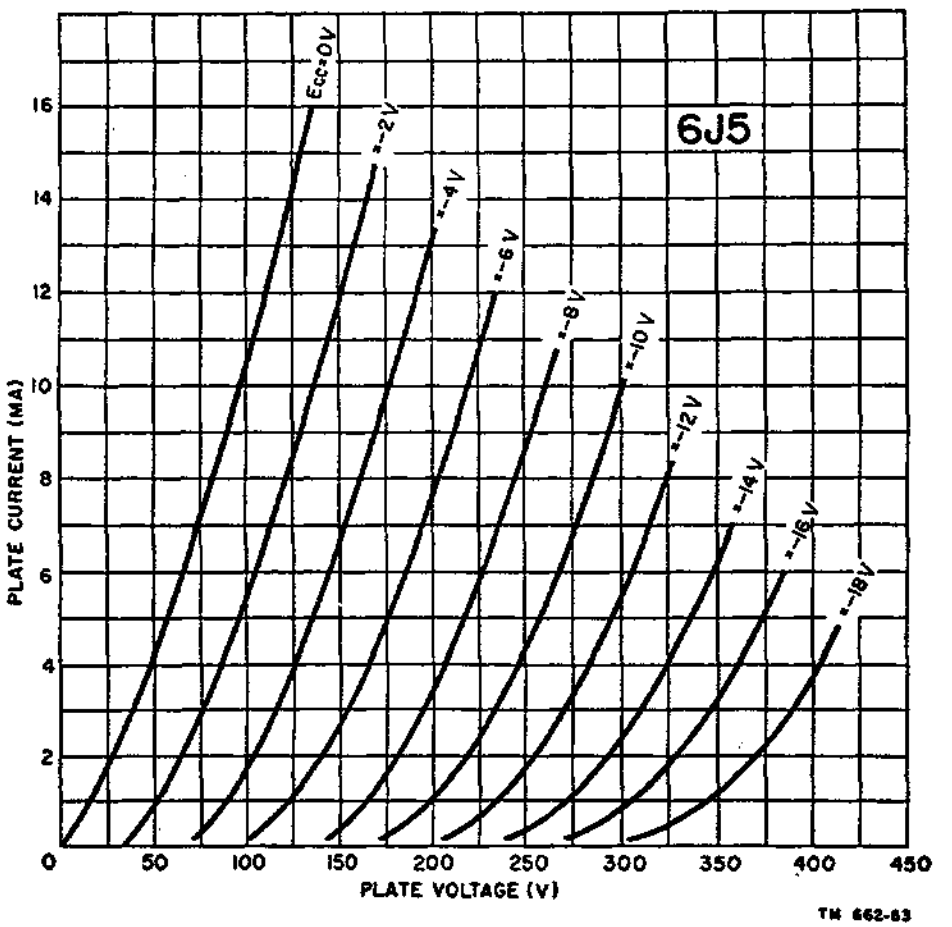


Figure 54. Plate family of characteristic curves for 6J5 triode.

rent for small increments of grid-voltage change and fixed differences in plate voltage, the plate family displays the effects of small increments of plate-voltage and fixed increments of grid-voltage. These family graphs serve to present the relationship between the different triode-tube electrode voltages under static conditions. They also lead to the meaning of tube *constants* or *parameters*, frequently described as tube rating data. Tube constants provide a means of comparing vacuum tubes and determining their suitability for specified functions.

45. Tube Constants

a. GENERAL. The behavior of the plate current in a triode (or in any vacuum tube which contains three or more electrodes), under the influence of different control-grid and plate voltages, does not occur at random. It is a function of the design of the tube—specifically, the geometric organization of the tube electrodes. Examples of these are the separation between the electrodes, the shape and dimensions of the electrodes, and other physical details. It is these factors which determine the maximum voltages that can be applied to the electrodes, the maximum plate current permissible through the tube, the conditions for plate current cut-off, and other similar facts. All of these are expressed by a group of numbers referred to as tube *constants*.

b. NAMES OF CONSTANTS. Tube constants differ from tube characteristics. Whereas the characteristic is a graphical representation of tube behavior under the particular set of conditions shown, the tube constants are individual numerical ratings predicated upon the geometry of the tube. Tubes possessing similar constants demonstrate similar relationships, although the specific values of grid voltage, plate voltage, and plate current necessary to make the tube perform properly may be different for the various tubes. The three primary tube constants are *amplification factor*, *a-c plate resistance*, and *transconductance*. Each of these will be explained.

46. Amplification Factor

a. DEFINITION. By definition, the *amplification factor* or *amplification constant* is the ratio between a small change in plate voltage and a small change in grid voltage which results in the same change in plate current. It is an indication of the effectiveness of the control-grid voltage relative to the plate voltage in controlling the plate current. Expressed in a formula

$$\text{Amplification factor} = \frac{\text{Small change in plate voltage}}{\text{Small change in grid voltage}}$$

or

$$\mu = \frac{\triangle e_b}{\triangle e_c} \quad (i_b \text{ constant}).$$

The amplification factor is represented by the Greek letter μ, pronounced mu. The Greek letter $\triangle$ indicates *a small change in*. It is a pure number without any reference to units. For example, if a tube is said to have a μ of 100, it means that the grid voltage change required to produce a certain change in plate current is 100 times less than the plate voltage change required to bring about the same change in plate current. In other words, the grid voltage is 100 times more effective than the plate voltage in its influence upon the space charge and, consequently, on the plate current. To illustrate, suppose that a plate-current change of 1 ma is produced by a plate-voltage change of 10 volts, and a grid-voltage change of .1 volt produces a 1-ma change in plate current. Then

$$\mu = \frac{10}{.1} = 100$$

and the amplification factor is 100. Emphasis is placed on the fact that it is the *change* in plate voltage and the *change* in grid voltage that are important and not the individual values of plate and grid voltage.

b. FINDING AMPLIFICATION FACTOR.

(1) The amplification factor can be determined by using either the grid or the plate family of curves. Using the grid family (fig. 55), assume that it is desired to determine the μ of the 6J5 with 250 volts on its plate and —8 volts on its grid. This corresponds to point A in the figure. The first step is to locate, on the curve of $E_{bb} = 250$ volts, some convenient point along the straight part of the characteristic, such as point B. Next, project a line parallel to the X-axis from point B to the adjacent curve of $E_{bb} = 200$ volts, which is point C. From point

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

EXTRACT

Paragraphs 45—57

United States Government Printing Office
Washington: 1952

rent for small increments of grid-voltage change and fixed differences in plate voltage, the plate family displays the effects of small increments of plate-voltage and fixed increments of grid-voltage. These family graphs serve to present the relationship between the different triode-tube electrode voltages under static conditions. They also lead to the meaning of tube *constants* or *parameters*, frequently described as tube rating data. Tube constants provide a means of comparing vacuum tubes and determining their suitability for specified functions.

45. Tube Constants

a. GENERAL. The behavior of the plate current in a triode (or in any vacuum tube which contains three or more electrodes), under the influence of different control-grid and plate voltages, does not occur at random. It is a function of the design of the tube—specifically, the geometric organization of the tube electrodes. Examples of these are the separation between the electrodes, the shape and dimensions of the electrodes, and other physical details. It is these factors which determine the maximum voltages that can be applied to the electrodes, the maximum plate current permissible through the tube, the conditions for plate current cut-off, and other similar facts. All of these are expressed by a group of numbers referred to as tube *constants*.

b. NAMES OF CONSTANTS. Tube constants differ from tube characteristics. Whereas the characteristic is a graphical representation of tube behavior under the particular set of conditions shown, the tube constants are individual numerical ratings predicated upon the geometry of the tube. Tubes possessing similar constants demonstrate similar relationships, although the specific values of grid voltage, plate voltage, and plate current necessary to make the tube perform properly may be different for the various tubes. The three primary tube constants are *amplification factor, a-c plate resistance,* and *transconductance.* Each of these will be explained.

46. Amplification Factor

a. DEFINITION. By definition, the *amplification factor* or *amplification constant* is the ratio between a small change in plate voltage and a small change in grid voltage which results in the same change in plate current. It is an indication of the effectiveness of the control-grid voltage relative to the plate voltage in controlling the plate current. Expressed in a formula

$$\text{Amplification factor} = \frac{\text{Small change in plate voltage}}{\text{Small change in grid voltage}}$$

or

$$\mu = \frac{\triangle e_b}{\triangle e_c} \quad (i_p \text{ constant}).$$

The amplification factor is represented by the Greek letter μ, pronounced mu. The Greek letter $\triangle$ indicates *a small change in.* It is a pure number without any reference to units. For example, if a tube is said to have a μ of 100, it means that the grid voltage change required to produce a certain change in plate current is 100 times less than the plate voltage change required to bring about the same change in plate current. In other words, the grid voltage is 100 times more effective than the plate voltage in its influence upon the space charge and, consequently, on the plate current. To illustrate, suppose that a plate-current change of 1 ma is produced by a plate-voltage change of 10 volts, and a grid-voltage change of .1 volt produces a 1-ma change in plate current. Then

$$\mu = \frac{10}{.1} = 100$$

and the amplification factor is 100. Emphasis is placed on the fact that it is the *change* in plate voltage and the *change* in grid voltage that are important and not the individual values of plate and grid voltage.

b. FINDING AMPLIFICATION FACTOR.

(1) The amplification factor can be determined by using either the grid or the plate family of curves. Using the grid family (fig. 55), assume that it is desired to determine the μ of the 6J5 with 250 volts on its plate and —8 volts on its grid. This corresponds to point A in the figure. The first step is to locate, on the curve of $E_{bb} = 250$ volts, some convenient point along the straight part of the characteristic, such as point B. Next, project a line parallel to the X-axis from point B to the adjacent curve of $E_{bb} = 200$ volts, which is point C. From point

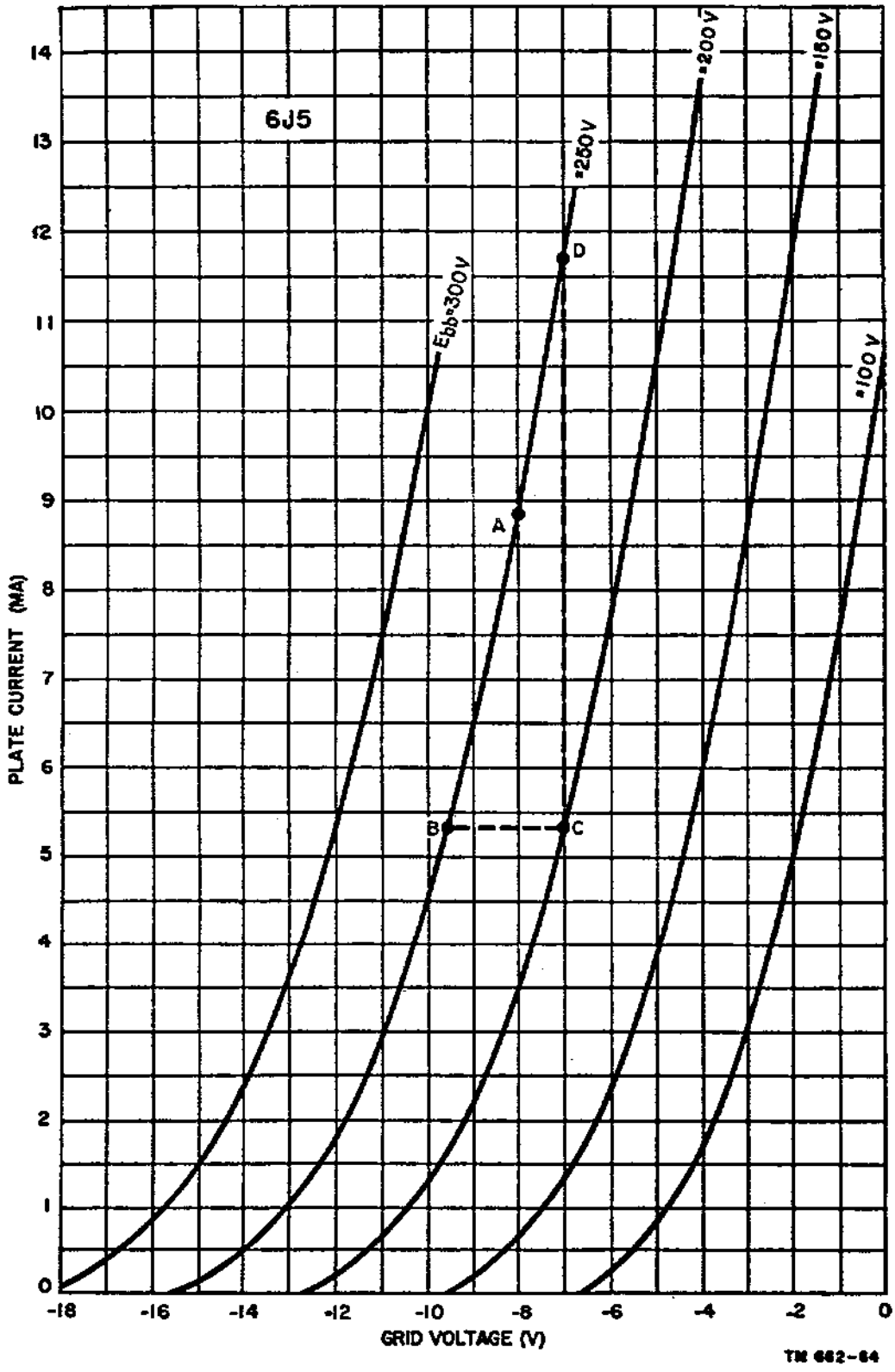


Figure 55. Grid family of curves used to determine amplifiaction factor of 6J5 triods.

C, project a line parallel to the Y-axis upward from the curve of E_{bb} = 200 volts until it intersects the curve of E_{bb} = 250 volts. This is point D.

(2) The plate current at D is 11.7 ma and at B it is 5.35 ma. Also, point D corresponds to a negative grid voltage of 7, and point B corresponds to a negative grid voltage of 9.6 volts. Consequently, with the plate voltage held constant at 250 volts and the grid voltage varying between points D and B—that is, from 7 to 9.6 volts, or a total change of 2.6 volts—the plate current changes from 11.7 to 5.35 ma or 6.35 ma. As to the plate-voltage change required to produce this same plate-current change, this value is found by holding the negative grid voltage constant at 7 volts and changing the plate voltage from D to C, that is, from 250 to 200 volts. Again, the plate current changes from 11.7 ma to 5.35 ma, or 6.35 ma.

(3) A recapitulation of the action shows that a 50-volt change in plate voltage results in a plate-current change of 6.35 ma, and a grid-voltage change of 2.6 volts produces the same 6.35-ma change in plate current. This can be summarized as

$$\mu = \frac{\triangle e_b}{\triangle e_c} = \frac{50}{2.6} = 19.20.$$

The amplification factor or μ of the tube is 19.2. This means that the grid voltage is 19.2 times more effective than the plate voltage in causing a change in plate current. This μ of 19.2 is only 4 percent less than the figure specified in the manufacturer's literature of the 6J5 triode. For all practical purposes, the μ of this triode can be considered as 20, since the 19.2 figure will vary slightly anyway on the nonlinear portions of the curves.

47. Finding μ from Plate Families

a. GENERAL. The amplification factor of a triode can be determined from the plate family of characteristics as well. Graphical determination of tube constants is accomplished more frequently by means of the plate family than the grid family because the latter is not shown too often in tube literature. A typical static plate family appears in figure 56.

b. DETERMINING AMPLIFICATION FACTOR.

(1) Developing the amplification constant of a triode from the plate family is a simple process. Select a grid-voltage value that is about halfway between the usable limits of the grid-voltage range shown on the graph. Referring to figure 56, —8 volts is a satisfactory grid voltage. Locate a reference point about halfway down the straight portion of the plate-current curve for that grid voltage. This is point A. A horizontal projection parallel to the plate-voltage axis shows point A as being equal to 5 ma. A vertical projection downward to the plate-voltage scale shows A to be equal to 216 volts. Point A, therefore, corresponds to E_{cc} = —8 volts, I_b = 5 ma, and E_{bb} = 216 volts.

(2) Now, project point A parallel to the X-axis to an adjacent grid-bias curve. The direction of this projection is optional. In this instance, it is toward the higher value of negative grid bias. This is point B at E_{cc} = —10 volts. A vertical projection dropped to the plate-voltage axis intersects the 257-volt point. Point B can, therefore, be described as E_{cc} = —10 volts, I_b = 5 ma, and E_{bb} = 257 volts.

(3) The next step is to project the higher plate-voltage point on the —8-volt curve; this results in point C. Point C corresponds to E_{cc} = —8 volts, I_b = 9.6 ma, and E_{bb} = 257 volts. The information needed to calculate μ has been obtained. With 216 volts on the plate (point A) to 257 volts on the plate (point C), a change in plate current from 5 to 9.6 ma takes place. With 257 volts on the plate, a change in grid voltage from —10 volts (point B) to —8 volts (point C) causes a change in plate current from 5 to 9.6

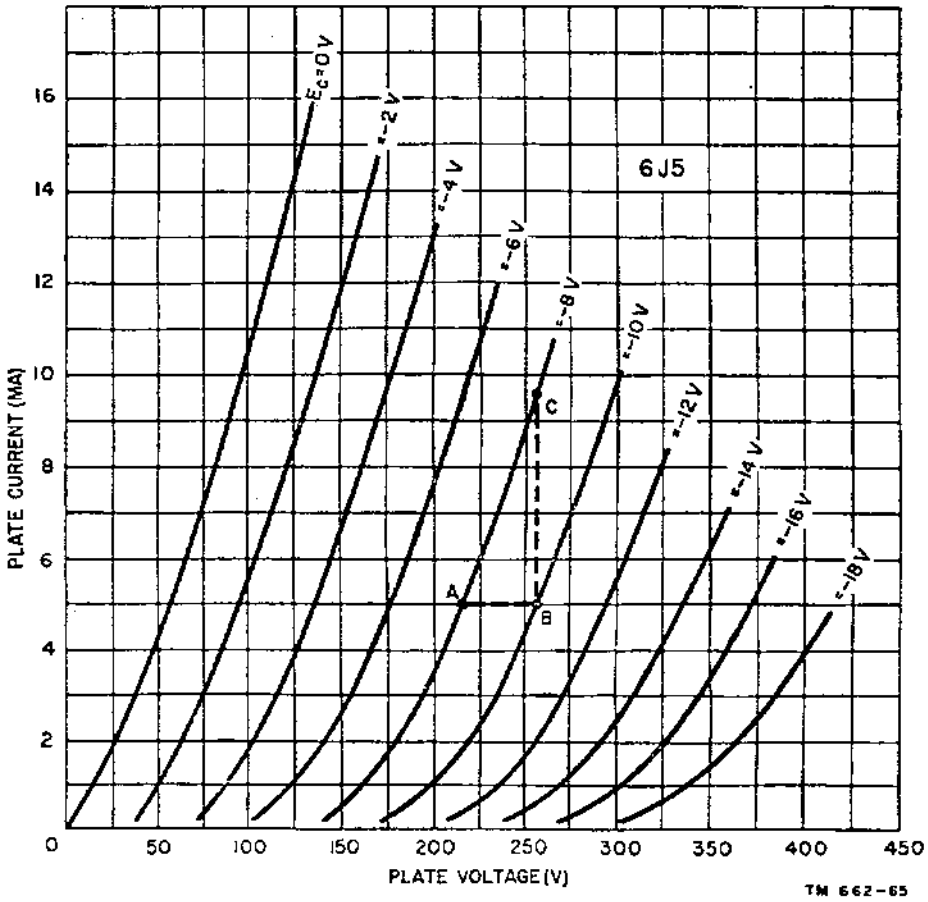


Figure 56. Plate family of curves used to determine the amplification factor of 6J5 triode.

ma. Therefore, the equation

$$\mu = \frac{\triangle e_b}{\triangle e_c} \text{ reads } \mu = \frac{257 - 216}{10 - 8} = \frac{41}{2} = 20.5$$

which is in substantial agreement with the data developed previously from the grid family. The constant determined by means of the plate family is closer to the manufacturer's data because the increments of change are smaller.

c. CLASSES OF TRIODES. There are three general classes of triodes: *low-μ triodes,* in which the amplification constant is less than 10; *medium-μ triodes,* in which it is between 10 and 30; and *high-μ triodes,* in which the amplification factor is 100 or more. A type of tube known as the *variable μ* possesses a changing μ feature.

48. Plate Resistance

a. DETERMINING R_P. The plate resistance is another vacuum-tube constant. It describes the *internal resistance* of the tube or the opposition experienced by the electrons in advancing from the cathode to the plate. This constant is expressed in two ways—the *d-c resistance* and the *a-c resistance.* The former is the internal opposition to current flow when *steady* values of voltage are applied to the tube electrodes, and is determined by the simple application of Ohm's law,

$$R \text{ (ohms)} = \frac{E \text{ (volts)}}{I \text{ (amperes)}}$$

at any point on the plate-current characteristic. The voltage, E, is the d-c plate voltage or E_{bb}, which equals e_b in this case, and the current, I, is the steady value of plate current of I_b. Resistance R, then, is R_p.

b. CALCULATING R_P. Referring to the plate

family in figure 57, point M is an arbitrary point corresponding to a plate voltage of E_{bb} — 250 volts, E_{cc} = —8 volts, and the plate current I_b — 8.9 ma. Applying Ohm's law,

$$R_p = \frac{250}{.0089}$$
$$= 28{,}100 \text{ ohms.}$$

For any value of plate voltage, the d-c resistance is determined by applying Ohm's law, where the numerator is the steady voltage at the plate, $e_b = E_{bb}$, and the denominator is the corresponding steady plate current. Point N in figure 57, therefore, corresponds to a d-c resistance of 37,500 ohms, since E_{bb} = 225 volts and I_b = 6 ma. Point 0 corresponds to a d-c resistance of 65,000 ohms. The various triangles in figure 57 can be neglected in establishing the d-c plate resistance; they are needed for finding the a-c plate resistance.

c. AC PLATE RESISTANCE

(1) Finding the a-c plate resistance from the plate family in figure 57 is somewhat more involved. The initial point Q on the curve marked E_{cc} = —10 volts, corresponds to a plate voltage of 285 volts and a plate current of 8 ma. The d-c resistance using Ohm's law is 33,100 ohms. The varying voltage representing a change of plate voltage for a-c resistance determination is obtained by varying the plate voltage above and below point Q. This operating range is shown by the small triangle drawn about Q. The total change in plate voltage is 20 volts, with the upper plate-voltage limit at 295 volts and the lower limit at 275 volts. The variations in plate voltage

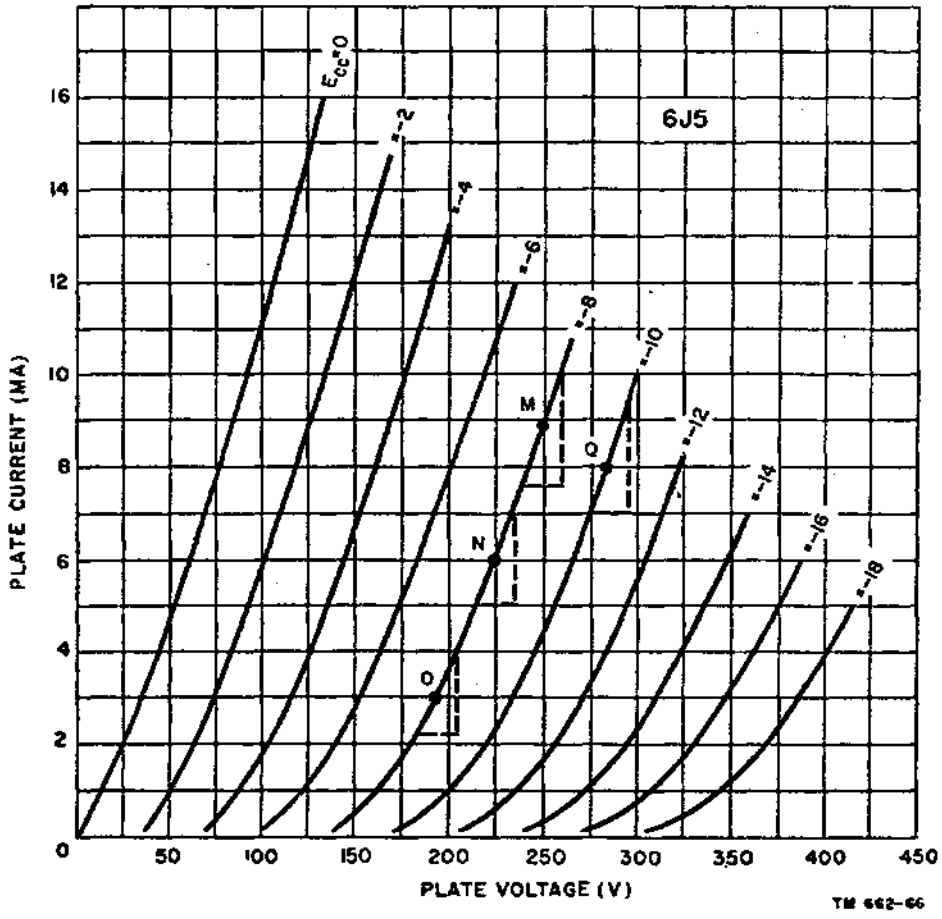


Figure 57. Plate family of curves used to determine a-c and plate resistance of 6J5 triode.

are arbitrary. The intersections with the appropriate grid-voltage curve are determined by projecting the voltage lines upward from the plate-voltage axis until they intersect the grid-voltage curve.

(2) The change in plate current, $\triangle i_b$, is determined by projecting the points of intersection between the —10-volt grid-voltage curve and the 295-volt and 275-volt plate-voltage lines, toward the left, to the plate-current axis. The upper and lower plate-current values are 9.4 ma and 7 ma, respectively. Consequently, the equation for the a-c plate resistance at the initial point Q is

$$r_p = \frac{\triangle e_b}{\triangle i_b} = \frac{295 - 275}{.0094 - .007} = \frac{20}{.0024} = 8{,}333 \text{ ohms.}$$

(3) This value does not agree exactly with the manufacturer's rating of 7,700 ohms, but it is sufficiently close for all practical purposes. As a matter of fact, the a-c plate resistance of a tube is a function of the operating point along the characteristic. This is shown by triangles M, N, and O in figure 57. Each represents a different operating point along the —8-volt grid-voltage curve. In each case, the plate voltage is changed by 10 volts each side of the operating point. For M, the r_p = 8,000 ohms, for N, r_p = 10,000 ohms, and for O, r_p = 11,100 ohms.

d. CONCLUSIONS. A comparison of the operating points discloses that the higher the applied plate voltage, the lower is the a-c plate resistance. Likewise, a change of the negative grid voltage in the positive direction causes a lower plate resistance. This is indicated by a comparison of the operating points M, N, O, and Q. In practice, one operating point is given, and the suitability of the tube is determined by the constants prevailing under the single set of conditions. As has been shown, each tube is capable of operation over a number of operating voltages, but only one of these is selected as being typical.

e. OTHER NAMES FOR R_P. Reference to *internal plate resistance* invariably means a-c rather than d-c resistance. Sometimes the term *plate impedance* is used to express a-c plate resistance. The two have the same meaning. It is to be noted that the a-c term involves *a small change* in plate voltage and *a small change* in plate current, which are stated in an equation as

$$r_p = \frac{\triangle e_b}{\triangle i_b} \ (e_c \text{ constant}).$$

The d-c resistance value, on the other hand, is predicated on steady values of plate voltage and plate current.

49. Transconductance (Mutual Conductance)

a. GENERAL. Changing the plate voltage or the grid voltage or both causes changes in plate current. There is a tube constant which expresses the specific change in plate current for a unit change in grid voltage, with the plate voltage held constant. This constant is known as the *transconductance* or *mutual conductance.* The former term has become the common standard.

b. DEFINITION.

(1) By definition, transconductance is the ratio of the change in plate current to the change in grid voltage which produced it, with the plate voltage held constant. In equation form, it is

$$g_m = \frac{\triangle i_b}{\triangle e_c} \ (e_b \text{ constant}).$$

(2) When related to the plate and grid circuits, the precise notation for transconductance is g_{pg}, but it has become common practice to refer to it by the letters g_m. When given a quantitative interpretation, transconductance is the milliampere change in plate-current-per-volt change in grid voltage.

c. NUMERICAL EXAMPLE. The unit of transconductance is the *mho* (*ohm* spelled backward), but since its value generally is too large for common usage in connection with vacuum tubes, the *micromho*, or the millionth part of the mho, is the usual reference. A mho corresponds to 1 μa (microampere) change in plate current for a 1-volt change in grid voltage, or 1 mho = 1,000,000 umho (micromhos). Conversion from mho to micromhos is accomplished

by multiplying the quantity expressed in mhos by 1,000,000. An electron tube which operates so that a 1-volt change in its grid voltage results in a 1-ma change in plate current is rated at a transconductance of 1,000 umho. Because of the single meaning, it has become customary to drop the word micromhos and to say simply that a tube such as that stated above has a transconductance of 1,000.

d. DETERMINING G_M GRAPHICALLY (fig. 58). Plate families of characteristic curves generally are more available than grid families. Therefore, it is desirable to know how to determine the transconductance of a tube from them. Since by definition the transconductance requires that the grid voltage be varied and the plate voltage remain constant, first select a point on a grid-bias curve which, when projected upward or downward vertically along a constant plate-voltage line, will intersect the adjacent grid-voltage curve. This is the initial point A, representing 235 volts on the plate and —8 volts on the grid. The plate current is 7.1 ma. A vertical projection from point A to the adjacent grid-voltage curve intersects the —6-volt curve and produces point B. The corresponding plate current is 12 ma and the plate voltage remains at 235 volts. The change in grid voltage occurs with the plate voltage constant. Substituting the plate-current and grid-voltage values in the equation, the transconductance is found to be

$$g_m = \frac{\Delta i_b}{\Delta e_c} = \frac{.012 - .0071}{8 - 6} = \frac{.0049}{2} = .00245 \text{ mho}$$

or 2,450 umho

Translated into plate-current change per 1-volt change on the grid, it amounts to 2.45 ma per volt. The abbreviation ma/v commonly is used in place of the words milliamperes per volt to express transconductance. Note how near this g_m value is to 2,600 which is given by the tube manufacturer. The slight discrepancy is due to the nonlinearity of the E_{cc} curves.

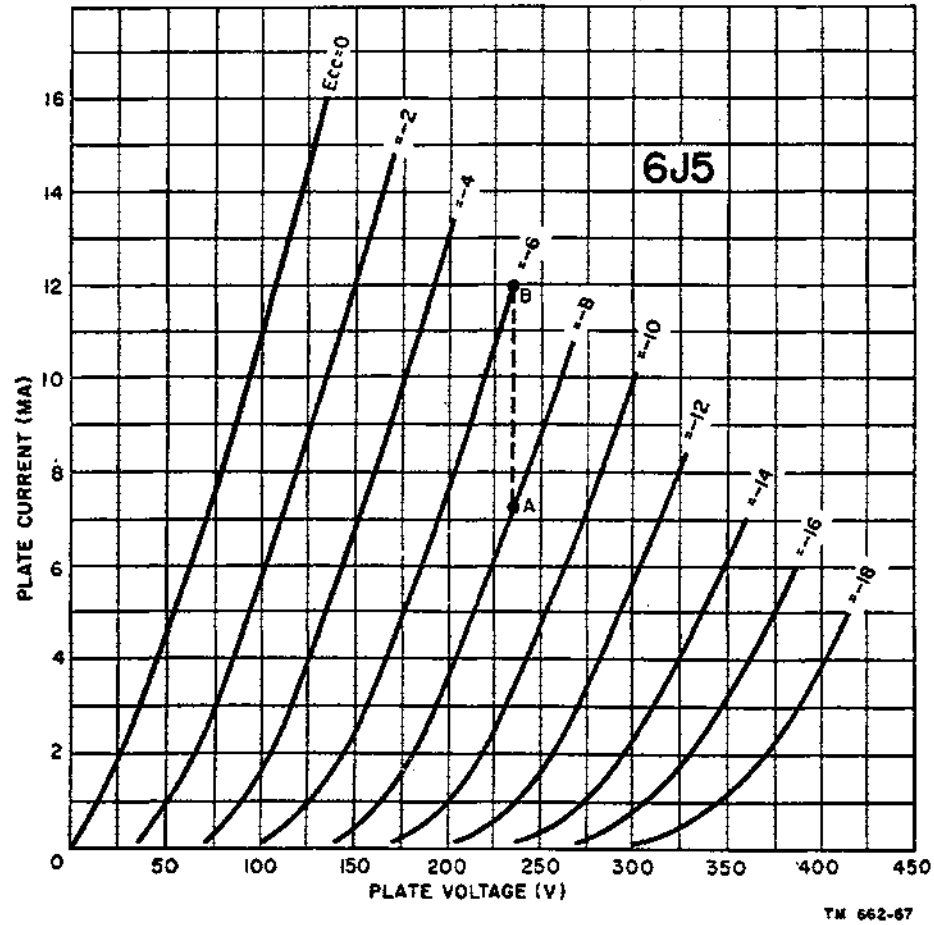


Figure 58. Plate family of curves used to determine transconductance of 6J5 triode.

e. EVALUATION OF G_M. The transconductance of a tube is an important tube constant. It is the most commonly used of all the constants when comparing tubes of like kind. A tube with a transconductance of 2,000 is a better tube than one rated at a transconductance of 1,000. The tube with the higher transconductance is capable of furnishing greater signal output than the tube with the lower transconductance, assuming like levels of signal voltage applied to the grid and like arrangements in the plate circuit.

50. Relation between μ, R_P, and g_M

a. GENERAL. The three triode tube constants—namely, amplification constant, μ, the a-c plate resistance, r_p, and the transconductance, g_m—are interrelated. The operating voltages applied to each type of tube determine the exact value of each constant, and for any one set of operating potentials to the electrodes each tube bears these three ratings. They vary in magnitude relative to each other in a definite manner. These data are illustrated in figure 59 for the 6J5.

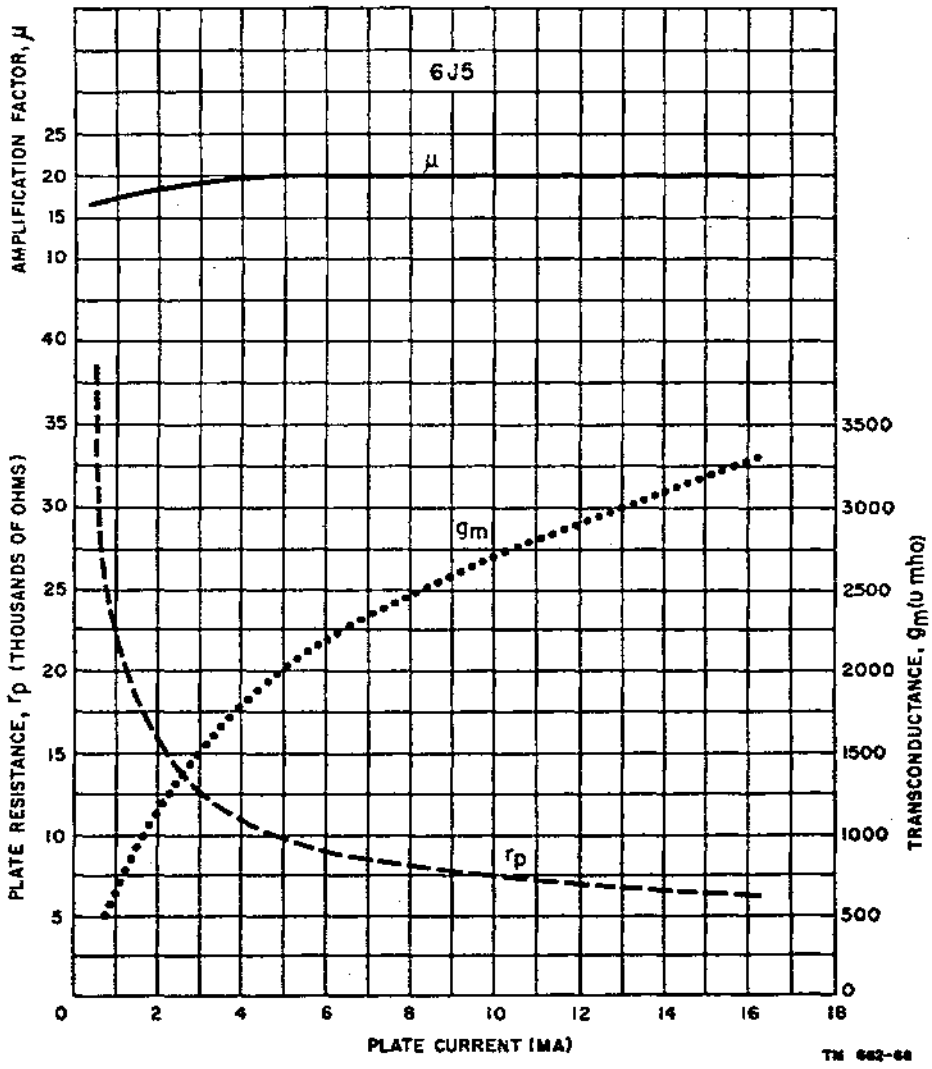


Figure 59. Curves showing relationships between μ, g_m, and r_p.

b. PLOTTING CONSTANTS. All three constants have individual Y-axis scales. As a reference, the plate current axis (X-axis) is common to all. When reading the values indicated upon the graph, the plate-resistance, r_p scale is shown on the lower left-hand Y-axis; the transconductance, g_m, appears on the right-hand Y-axis, and the amplification constant, μ, is on the upper vertical left-hand Y-axis.

c. GENERAL RELATIONSHIPS.

(1) Concerning the relationship between the constants, the amplification factor remains substantially constant under virtually all conditions. Being a property of the physical geometry of the tube, it varies little with changes in the operating voltages applied to the grid and the plate.

(2) Plate resistance, r_p, on the other hand, varies greatly with operating voltages, especially through the region of potentials which result in low values of plate current. This occurs at high negative grid bias or low plate voltage, or both. It is significant that increasing the physical separation between grid and plate in a triode results in a high amplification factor, also in a high a-c plate resistance. Usually, therefore, although not invariably, the higher the amplification constant of a triode, the higher the a-c plate resistance of that tube.

(3) As to the transconductance, it is seen to vary oppositely to a-c plate resistance; given any tube, the higher the plate resistance, the lower the g_m, and vice versa. All triodes with high transconductance ratings have low a-c plate resistance.

d. MATHEMATICAL RELATIONSHIPS.

(1) Following is the mathematical relationship that exists between the three constants. Since,

$$\text{amplification constant } (\mu) = \frac{\triangle e_b}{\triangle e_c}$$

$$\text{a-c plate resistance } (r_p) = \frac{\triangle e_b}{\triangle i_b}$$

$$\text{transconductance } (g_m) = \frac{\triangle i_b}{\triangle e_c}$$

and the term $\triangle i_b$ appears in both the r_p and g_m formulas, they can be made equal to each other; that is,

$$\triangle i_b = g_m \times e_c = \frac{\triangle e_b}{r_p},$$

resulting in

$$r_p \times g_m = \frac{\triangle e_b}{\triangle e_c}.$$

But $\mu = \frac{\triangle e_b}{\triangle e_c}$ also; therefore, the product of the a-c plate resistance and the transconductance is equal to the amplification constant. That is, $\mu = r_p$ times g_m or, by simple transformation, $r_p = \mu/g_m$ and $g_m = \mu/r_p$.

(2) Substituting the values for r_p and g_m that were previously obtained, by using $r_p = 8{,}333$ ohms and $g_m = 2{,}450$ umho, μ can be calculated as follows:

$$\mu = r_p \times g_m$$
$$= 8{,}333 \times .00245 = 20.4$$

which is in substantial agreement with the original value of 20.5. The accuracy of the constants varies because they are not read to the same decimals on each of the graphs, nor at exactly the same point. The a-c plate resistance is

$$r_p = \frac{\mu}{g_m}$$
$$= \frac{20.5}{.00245}$$
$$= 8{,}360 \text{ ohms}$$

and the transconductance is

$$g_m = \frac{\mu}{r_p}$$
$$= \frac{20.5}{8{,}340}$$
$$= .00246 \text{ mho.}$$

e. DISCREPANCIES PRESENT. The discrepancies present in the r_p and g_m values stem from the degree of accuracy present on the graphs. Errors of a few percent are unimportant and do not cause any complication. Moreover, the purpose of these calculations is to show how information contained in tube literature can be used for the development of unknowns, rather than to attempt to verify the information obtained from the graphs.

f. PURPOSE OF CONSTANTS. With reference to the constants of the triode, it is timely to say that these coefficients of tube behavior are not restricted to the triode only. They apply to all electron tubes which contain three or more electrodes. The 6J5 tube discussed in this chapter is just one example. Other triodes can have the same values of μ, r_p, and g_m, whereas some tubes may differ substantially. The important points to remember are that tube constants are a means of comparing tubes of like type; also, that they serve in selecting tubes to fit specific needs.

51. Dynamic Characteristics of Triode

a. GENERAL.

(1) The static characteristic of an electron tube provides an understanding of how it operates. For the information to have practical value, it must be translated into data which are related directly to an application.

(2) This requirement alters the fundamental circuit of the triode system, and in doing so, gives rise to a new set of characteristics. These are called *dynamic* characteristics. In the final analysis, they are the important ones rather than the static characteristics. The latter are used as a means for creating the familiarity necessary for comprehension of the behavior of the triode (and other electron tubes) as used in actual practice. All other exploration of how an electron tube works is done by means of the dynamic characteristics.

b. LOAD RESISTOR.

(1) The difference between an electron-tube system which allows determination of the static characteristics and a system which allows determination of the dynamic characteristics is not too great. In fact, it is a relatively minor change physically, although it is a major change relative to the actions occurring in its circuity. The dynamic characteristics can be described as a graphic portrayal of tube behavior under *load* (fig. 60). A shows the basic triode circuit containing a load and, for comparison, the basic triode circuit without a load is shown in B.

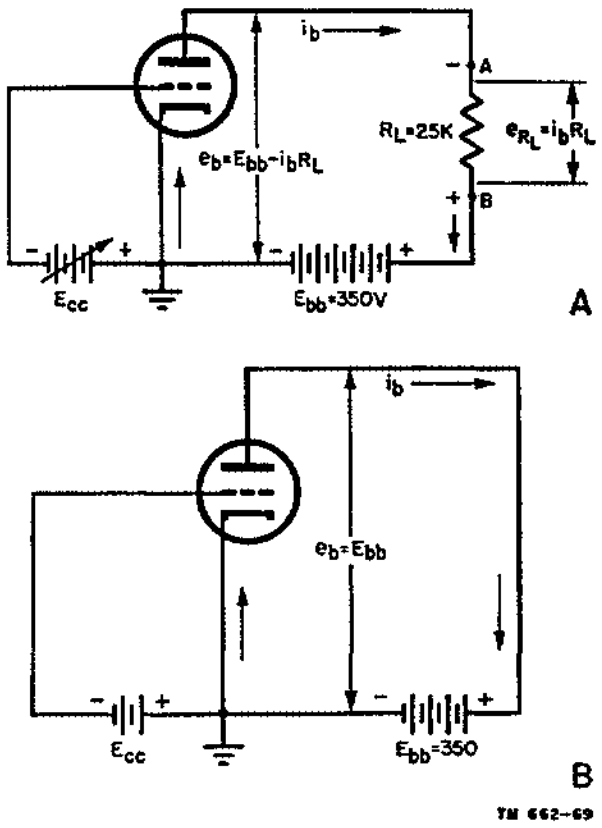


Figure 60. Basic circuit of triode with and without load.

(2) One difference will be noted in these two basic circuits. In A, the presence of the resistor, R_L, is designated as the *load resistance.* It is located in the plate circuit external of the tube. It is in series electrically with the plate-voltage supply, E_{bb}, and the plate of the tube; consequently, the plate current must pass through R_L. This action greatly modifies the operating characteristics of the tube. It does not alter the three basic constants of the tube, but it does affect the plate-current grid-voltage characteristics.

c. USE OF LOAD RESISTOR. From a practical viewpoint, the circuit in A contains the essential elements for practical use of the triode. For an electron tube to be usable for any purpose what-

soever, it requires a load. The variations in plate current caused by a varying voltage applied to the control grid appear across the load as a varying voltage drop. Under proper conditions of use, the changing voltage across the load is the *output* signal. It is a replica, smaller or greater, as the case may be, of the varying voltage applied to the control grid.

d. LOAD CURRENT. The plate circuit contains several new terms, since a new action is described. To understand these new terms, it is imperative to note the plate resistor and its location. Load resistor R_L is directly in the path of plate current i_b. The movement of electrons comprising the plate current must be through this resistor, because the complete plate-current circuit is from cathode to the plate inside the tube, and, on the outside of the tube, through resistor R_L to the positive terminal of the battery, E_{bb}, and from the negative terminal of E_{bb} to the cathode.

e. CIRCUIT VOLTAGES.

(1) Under these circumstances, two voltage drops occur in the plate circuit. One of these is across the internal resistance of the tube, or $i_b r_p$, and the other is the drop across R_L, or $i_b R_L$. This leads to three voltages being present in the plate circuit: E_{bb} — the voltage available from the plate-voltage supply; e_b — the instantaneous voltage available from plate to cathode. This voltage is the difference between supply voltage E_{bb} and the voltage drop across load R_L, or $e_b = E_{bb}$ minus $i_b R_L$. Whether e_b is instantaneous or steady is determined by the character of the plate current, which relates back to the grid voltage; e_{RL} (the voltage drop across the load resistor R_L) $= i_b R_L$.

(2) In A of figure 60, assume that the grid voltage, E_{cc}, is adjusted to such a high negative value as to cut off plate current i_b. In that event, voltage e_b across the internal resistance of the tube (between plate and cathode) is the same as the plate-supply voltage, or $e_b = E_{bb} = 350$ volts, shown in B. This is true because with the plate current cut off there is no voltage drop across R_L. The internal plate resistance is infinite and the finite value of 25,000 ohms in series with an infinite resistance has no significance when this action occurs.

(3) Now assume that the control-grid voltage is changed so that 1 ma of current flows in the plate circuit, or $i_b = .001$ ampere. Supply voltage E_{bb} is constant at 350 volts, at which value it remains regardless of the amount of plate current that flows. With .001 ampere of plate current, the voltage drop across R_L is

$$i_b R_L = .001 \times 25{,}000$$
$$= 25 \text{ volts.}$$

Since the voltage between the plate and cathode or the voltage drop across the internal resistance of tube r_p is the difference between the supply voltage and the voltage drop across R_L,

$$e_b = E_{bb} - i_b R_L$$
$$= 350 - 25$$
$$= 325 \text{ volts.}$$

Apparently most of the voltage drop takes place across the internal plate resistance, which now is finite since plate current flows. The voltage from plate to ground is high and the voltage across the load is relatively low.

(4) Now assume a change in grid voltage which causes the flow of 12 ma of plate current. By Ohm's law the voltage drop across the load is

$$e_{RL} = i_b R_L = .012 \times 25{,}000$$
$$= 300 \text{ volts}$$

and voltage e_b at the plate, or across the internal resistance of the electron tube, is

$$e_b = E_{bb} - i_b R_L$$
$$= 350 - 300$$
$$= 50 \text{ volts.}$$

During such operating conditions, most of the voltage drop occurs across load R_L and very little drop appears across the internal plate resistance of the tube; that is, the voltage from plate to cathode is relatively low.

(5) Bearing in mind that the plate-supply voltage, E_{bb}, is always constant at 350 volts, and that the change in plate cur-

rent is a function of the control-grid voltage, it is possible to imagine such an increase in plate current that all of the voltage drop in the plate circuit occurs across load R_L. If this occurs, the distribution of voltages in the plate circuit would be such that voltage e_b would be 0. This is an extreme condition and cannot occur in actual practice. The plate current may rise sufficiently that the effective voltage between plate and cathode is very low but never 0, since a drop always appears across r_p, even though it may be considered negligible.

f. EFFECT OF LOAD RESISTOR. All of these changes in effective plate voltage e_b result from the presence of load resistor R_L. The moment plate current flows, regardless of its value, the load resistance comes into play and affects the effective plate voltage. The load resistance reduces the effective plate voltage under all conditions of plate current except 0. This means that with a load present in the plate circuit, the actual change in plate current for a change in grid voltage is much less than it would be if load R_L were not present. This becomes evident upon consideration of the reduction in effective plate voltage simply because of the presence of a voltage drop across load R_L as soon as current flows.

g. DIFFERENCE BETWEEN CHARACTERISTICS. The relationship between grid voltages and plate current with the load present is called the *dynamic* characteristic. It differs from the static characteristic because the effective plate voltage, e_b, is not equal to the plate-supply voltage, E_{bb}, when plate current flows, as with static characteristics.

52. Load Line

a. GENERAL.

(1) The effect of the load applied to a triode (and other electron tubes) can be predicted in advance. This usually is accomplished by adding to the static plate family of characteristic curves (fig. 54) a graphical representation of the load, known as the *load line.* This shows the distribution of the output of plate-voltage supply E_{bb} between the load and the internal resistance of the tube under different conditions of plate current.

(2) For convenience, the plate family of characteristic curves is used for the dynamic characteristics. From it is developed the final transfer characteristic curve which correlates the plate-current grid-voltage relationship with the load present in the circuit. This curve is called the dynamic transfer characteristic. It is to be noted, however, that equal information can be obtained from the dynamic plate characteristic and from the dynamic transfer characteristic.

b. SELECTING LOAD LINE.

(1) Figure 61, showing a typical static plate family of curves, is the same as figure 54, except for the diagonal line XY, the load line. The load line corresponds to a load R_L of 25,000 ohms (A of fig. 60). The selection of 25,000 ohms is arbitrary. It can be a higher or a lower value, except that there are limits to the ohmic values of loads relative to the internal plate resistance of a tube, and also because of the fixed value of the applied plate voltage. These statements will be clarified later in discussions of voltage and power amplification.

(2) No connection exists between load line XY (fig. 61) and the static plate family. The load line has no fixed association with tube constants or characteristics. It is simply a means of developing information concerning the behavior of any tube that is used with a certain load. The load may be correct, or it may not be right for the tube. This information appears on the graph when the effects of the load are studied by means of the load line.

c. DISCUSSION OF LOAD LINE.

(1) The full length of the line represents one extreme condition — namely, a voltage drop across R_L equal to the full plate-supply voltage. This means

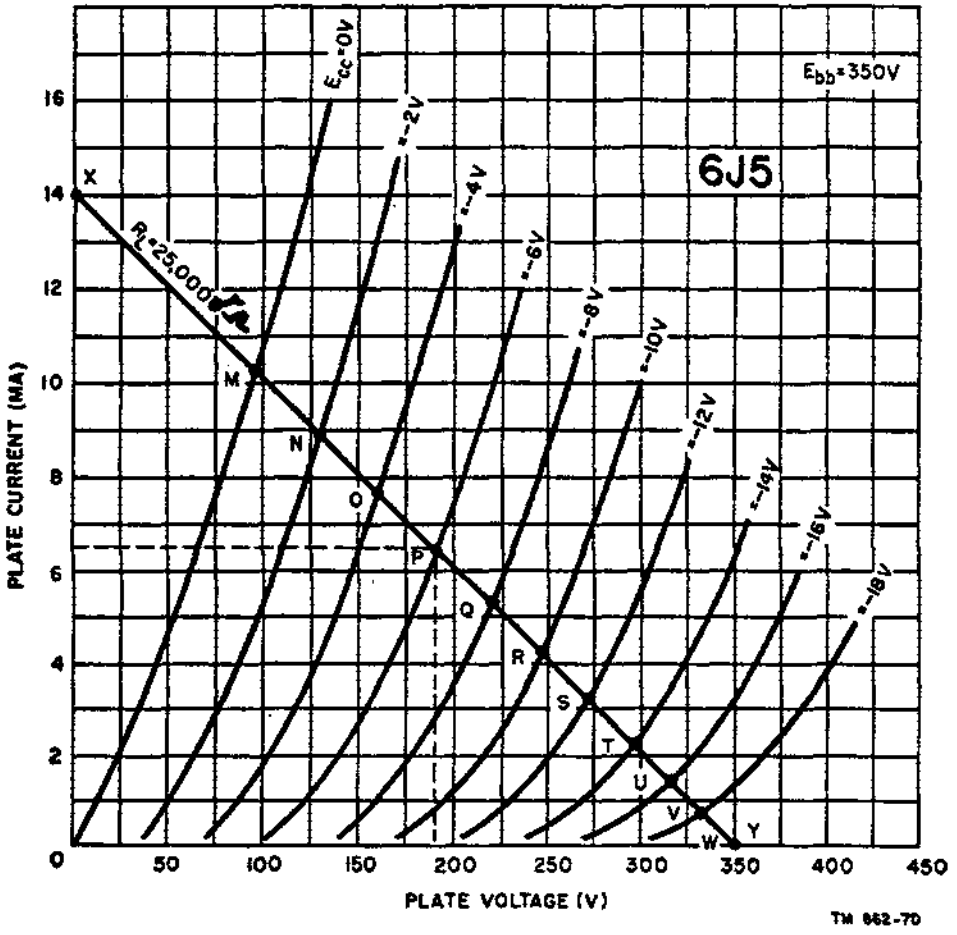


Figure 61. Plate family of characteristic curves for 6J5 triode, including load line.

that e_b = 0 and the plate current equals the full plate-supply voltage divided by the load resistor or

$$I_b = \frac{E_{bb}}{R_L} = \frac{350}{25{,}000}$$

$$= .014 \text{ ampere}$$

$$= 14 \text{ ma.}$$

This figure establishes one terminal of the load line—14 ma on the plate-current axis, point X. The other terminal of the load line corresponds to the other extreme condition: that is, zero plate current and the full plate-supply voltage of 350 volts on the plate of the tube. This is point Y on the plate-voltage axis.

(2) Further reference to figure 61 discloses that the load line intersects the plate-current curves at different points. To establish the distribution of voltages between the tube and the load, an operating point must be selected. Assume that the grid voltage chosen for examination is —6 volts, or E_{cc} = —6. The load line crosses the plate-current curve for this bias at point P. A horizontal line drawn to the plate-current scale shows that the corresponding plate current is 6.35 ma. A vertical line dropped from point P to the plate-voltage axis intersects it at 190 volts. Therefore, point P can be described as

$$E_{cc} = -6 \text{ volts}$$
$$E_{bb} = 190 \text{ volts}$$
$$i_b = 6.35 \text{ ma.}$$

The vertical projection to the plate-

voltage axis indicates the division of the plate-supply voltage across the load and across the internal resistance of the tube. The point of intersection between the horizontal projection to the plate-voltage scale and the axis indicates the voltage—190 volts—effective at the plate. The difference between this value and the total plate-supply voltage is the voltage dropped across the load, or 350 minus 190 = 160 volts. Further to verify this last statement, the voltage drop across the load resistor can be computed as follows

$e_{RL} = i_b R_L = .00635 \times 25{,}000 = 160$ volts.

(3) The voltage on the plate and the voltage dropped across the load, for various values of grid voltage, can be determined in similar fashion. For example, point M, corresponding to 0 voltage on the control grid or $E_{cc} = 0$, can be described as

$E_{cc} = -0$ volt
$i_b = 10.1$ ma
$e_b = 97$ volts
$e_{RL} = 253$ volts
$E_{bb} = 350$ volts.

Having selected $E_{cc} = -6$ volts as the operating point and $E_{cc} = 0$ volts as one extreme, the other extreme can be 6 volts in the other direction, or $E_{cc} = -12$ volts. This is point S and can be described as

$E_{cc} = -12$ volts
$i_b = 3.1$ ma
$e_b = 272$ volts
$e_{RL} = 78$ volts
$E_{bb} = 350$ volts.

d. SUMMARY AND CONCLUSIONS.

(1) The three points of intersection, M, P, and S, establish a number of operating factors. For instance, $E_{cc} = -6$ was selected as the reference operating point. Then an extreme condition, $E_{cc} = 0$ volts, was selected as one limit of change in grid voltage. The second limit of change in grid voltage was set as $E_{cc} = -12$ volts. How have these changes affected the plate circuit? The answer is given in the tabulation which follows.

$E_{cc} = 0$ v	$E_{cc} = -6$ v	$E_{cc} = -12$ v
$i_b = 10.1$ ma $e_b = 97$ v $e_{RL} = 253$ v	$i_b = 6.35$ ma $e_b = 190$ v $e_{RL} = 160$ v	$i_b = 3.1$ ma $e_b = 272$ v $e_{RL} = 78$ v

(2) From the data available in the preceding tabulation, other factors can be determined as shown below:

Change from $E_{cc} = 0$ to $E_{cc} = -6$ v	Change from $E_{cc} = -6$ to $E_{cc} = -12$ v
At plate from 190 — 97 = 93 v Across load from 253 — 160 = 93 v	At plate from 272 — 190 = 82 v Across load from 160 — 78 = 82 v

As shown in the preceding tabulation, the change in plate voltage e_b is not the same for equal changes in grid voltage. That is, making the grid less negative by 6 volts (going from —6 to 0) causes a fall in the effective plate voltage by 93 volts. However, when the grid was made more negative by 6 volts (going from —6 to —12), the effective plate voltage increases by only 82 volts. Under ideal conditions (such as having perfectly linear characteristic curves), the rise and fall in voltage at the plate would be the same in both directions. It is not the same in this case because of the curvature in the plate-current characteristics over the range of grid voltages between —6 and —12 volts. The curvature reduces the change in plate current per increment of increase in negative grid voltage beyond approximately —8 volts, where the curvature is more predominant. This situation introduces another subject for discussion—namely, linearity of the resultant characteristic — but this is set aside for later discussion.

(3) Another pertinent fact is that the total change in voltage at the plate always

is equal to the change in voltage across the load. This is shown in the tabulation in (2) above. A 93-volt change in e_b is equaled by a 93-volt change in e_{RL} when the grid voltage is varied from —6 volts to 0 volt. An 82-volt change in e_b is equaled by an 82-volt change in e_{RL} when the grid voltage is increased from —6 to —12 volts.

e. CHANGES IN GRID VOLTAGE.

(1) This is an appropriate time to inject another view of the change in voltage drop across the load. Assuming a slow manual means for changing the grid voltage, the changes in plate voltage as well as the changes in voltage drop across the load R_L would occur at the same rate. Regardless of how slowly or rapidly this takes place, the fact remains that it is a swing in voltage. In one direction the peak amplitude is 93 volts and in the other direction it is 82 volts. This change in voltage frequently is described as the swing in voltage, and is referred to as the peak value expressed in volts.

(2) A single expression of the peak value does not suffice for the example under discussion because of the nonlinear changes above and below the reference —6-volt grid voltage. The expression *swing in voltage* is usable, nevertheless, except that two peak values must be mentioned, a positive and a negative value. A single peak reference is usable when the changes are in only one direction.

53. Dynamic Transfer Characteristic

a. The load line shown on a static plate family tells a great deal, but not as conveniently as does another organization of characteristics. This is the static family of plate-current grid-voltage curves to which is added the effects of the load. The resultant plate-current grid-voltage curve is known as the dynamic transfer characteristic (fig. 62). It has become common practice, when studying the behavior of the plate current under the influence of a signal voltage applied to the grid, to show the dynamic transfer characteristic and to plot the input signal and the resultant plate current along this characteristic.

b. In figure 62, A repeats the static grid family illustrated in figure 53, and B shows the 25,000-ohm load line on the static plate family. The latter will be projected on the former to show the plate-current grid-voltage curve which represents the plate current corresponding to certain grid voltages and the effect of the load in creating the effective plate voltages.

c. The two families of curves have three attributes in common: a common plate-current axis, like values of control-grid voltage, and like values of plate-supply voltage, although the last two named are illustrated differently. In order to project the effect of the load line in B on the static grid family in A of figure 62, it is necessary to plot, on the latter graph, the plate-current values for each value of grid voltage shown on the plate family.

d. This is done in the following manner. Point M, in B of figure 62, corresponds to E_{cc} = 0 and 10.1 ma. This locates point M′ on the e_c = 0 grid-voltage line at the 10.1-ma point. Point N on the plate-family graph corresponds to E_{cc} = —2 volts and 8.9 ma and this locates point N′ on the intersection of the appropriate plate-current and grid-voltage projections on the grid-family graph. In similar fashion, points O, P, Q, R, S, T, U, and V on the plate family are transferred to the grid family. When these points are formed, the result is the characteristic curve M′, N′, O′, P′, Q′, R′, S′, T′, U′, V′. This is the *dynamic transfer characteristic.*

e. The dynamic transfer characteristic is seen to differ substantially from the static characteristic. It is much less steep and shows that a change in grid voltage results in a smaller change in plate current than does any static characteristic. This is not a disadvantage, although it may appear so at first glance, because the change in plate current for a given change in grid voltage on both sides of a reference point is much more linear with the load present than with the load absent.

f. For example, if the reference point is O′, which corresponds to —4 volts on the grid and 7.6 ma plate current, a change in grid voltage to —2 volts and then to —6 volts results in 8.9 and 6.4 ma of plate current. This is an

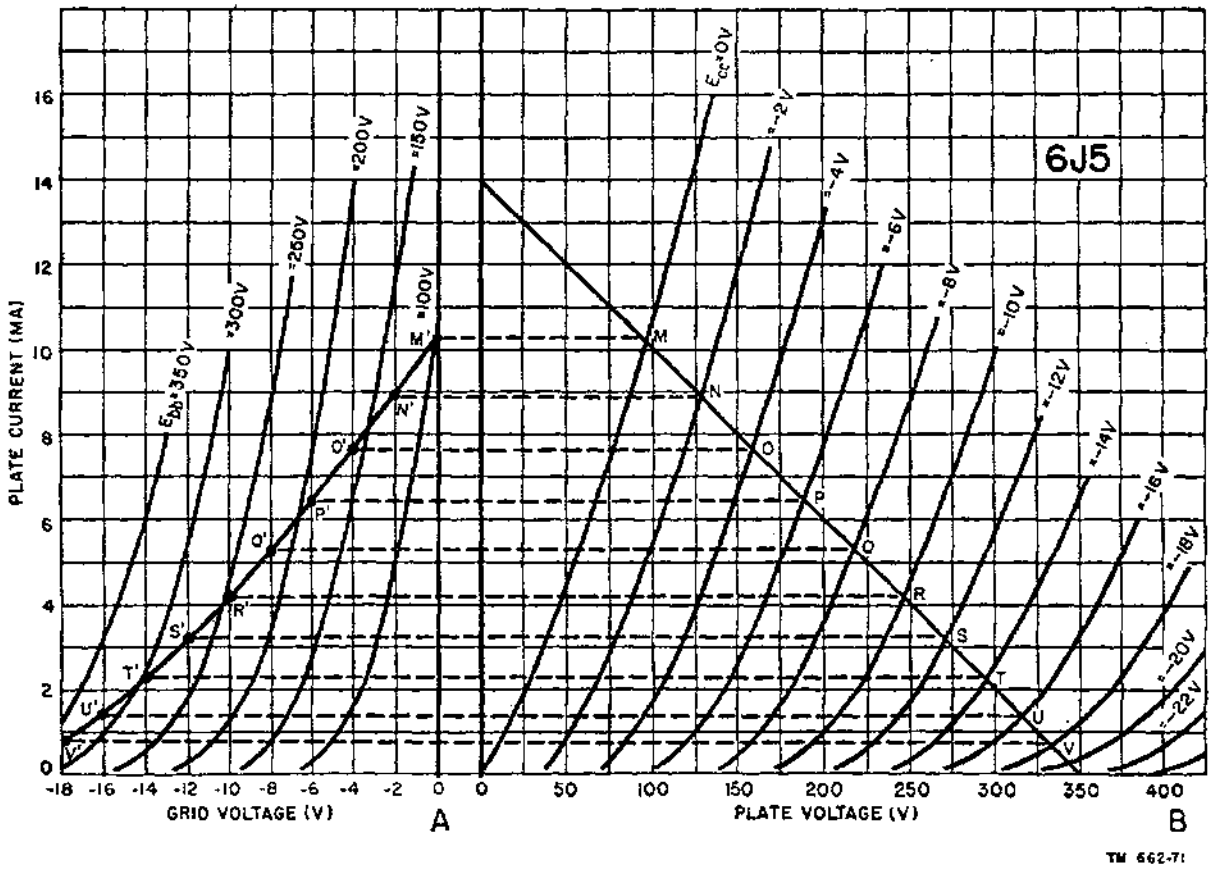


Figure 62. Plate and grid families of 6J5 which are used to construct dynamic tranfer characteristic.

increase of 1.3 ma in the positive direction and 1.2 ma in the negative direction. The swing in plate current is not linear, but the degree of nonlinearity is less than 8 percent even with the limited accuracy which is possible in graphs of this kind.

g. A corresponding point of operation along a static characteristic without any load is selected on the 150-volt curve. With —4 volts applied to the grid, the plate current is 6.4 ma. With the grid reduced to —2 volts, the plate current rises to 12 ma, a change of 5.6 ma. With the grid voltage changed to —6 volts, the plate current drops to 2.6 ma, a change of 3.8 ma. Nonlinearity between the positive and negative changes amounts to approximately 30 percent. Nonlinearity in electron tube behavior is a source of distortion and highly undesirable. Some value of distortion can be tolerated, but it always must be kept within the bounds permitted by the function of the system wherein the tube is being used. Too much distortion can destroy the usefulness of a complete system.

h. The dynamic transfer characteristic in A of figure 62 is seen to have some curvature. It is greater between approximately $e_c = -10.5$ volts and $e_c = -18$ volts than between $e_c = 0$ volts and $e_c = -10.5$ volts. Since linearity of plate-current changes is a general requirement, examination of the dynamic transfer characteristic discloses the range of grid voltages over which linearity in plate-current changes is available.

54. Effect of Different Loads

a. Before showing how the dynamic transfer characteristic is used with a simple triode amplifier system, it is necessary to dwell briefly on the subject of different loads. It was said that the selection of 25,000 ohms for 6J5 triode operated at a supply voltage of 350 volts was arbitrary when used in the circuit of figure 62.

It was seen also that the presence of a finite load produced a dynamic transfer characteristic which had some curvature or nonlinearity, although it was an improvement over the static plate-current grid-voltage without any load.

b. As apparent from the statements above and shown in figure 63, the higher the ohmic value of the load, the straighter should be the dynamic transfer characteristic. As the ohmic value of the load is increased, the over-all characteristic approaches a straight line; that is, it becomes more and more linear throughout its length. This can be seen by comparing characteristics A, B, C, and D. The curve for R_L = 100,000 ohms is substantially straight for almost its full length, whereas the curve for R_L = 25,000 ohms is straight for only a small portion, and that for R_L = 15,000 ohms is straight for even a smaller segment of the characteristic. The reason for this behavior is that the higher the load resistance (within a reasonable value of ohms), the greater the effect of the load in determining the plate current per unit of change in grid voltage and plate voltage rather than the change in internal plate resistance. With infinite load, the characteristic would be along the 0 plate-current line, because changes in grid voltage would have no effect on the circuit.

55. Simple Triode Amplifier

a. GRID SIGNAL. Previous discussions in this chapter have led to the explanation of the simple triode amplifier, shown schematically in figure 64. This amplifier is similar to the triode systems shown previously when they were used for the construction of static and dynamic characteristics, but it contains one important difference. This is the addition of a sine-wave signal source which generates the signal voltage e_g that is to be amplified. Signal e_g appears in the input circuit as a sinusoidal variation of voltage between the control grid and the E_{cc} supply. An amplified version of the signal re-

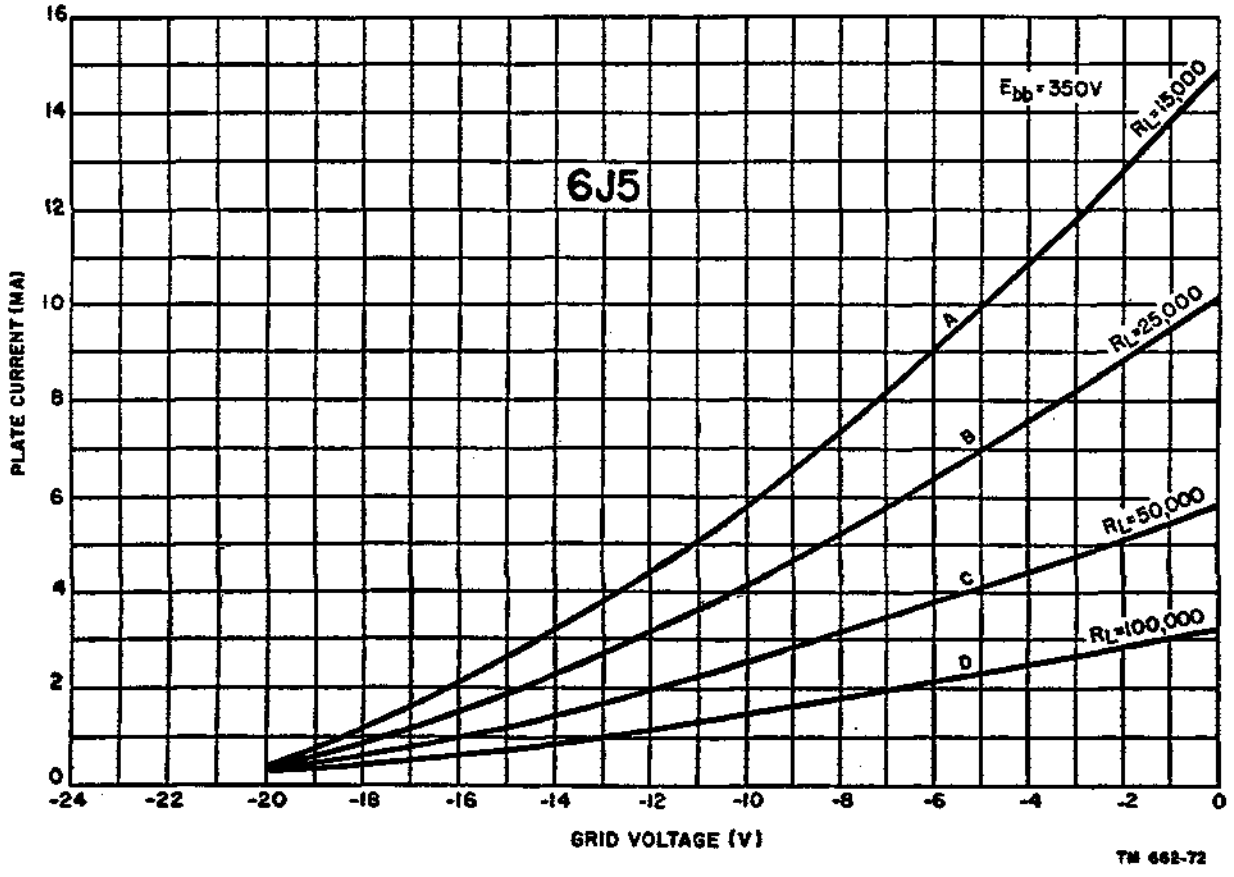


Figure 63. Dynamic transfer characteristic curves for different loads.

appears in the plate circuit as the varying drop, e_{RL}, across the load resistance. As described previously, this voltage drop developed across the load is the result of the varying plate current, i_b, that flows through the load.

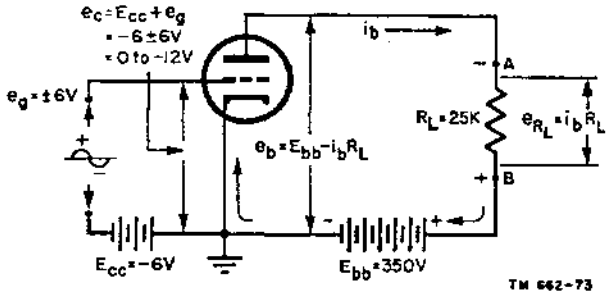


Figure 64. Basic circuit of triode, including input signal and load.

b. GRID VOLTAGES.

(1) By examination, three significant voltages now are present in the control grid-cathode circuit:

E_{cc} = the bias voltage
e_g = the instantaneous value of signal voltage
e_c = the instantaneous voltage between grid and cathode.

(2) The relative values of grid bias E_{cc} and signal voltage e_g warrant only brief comment at this time because the operation of this amplifier is explained in a later chapter. If the assumed requirement is that the triode amplifier must operate without grid current, the amount of the fixed grid bias, E_{cc}, must be at least equal to the peak value of the positive half of the sine-wave signal, e_g. In that way, the positive alternation of the signal voltage will not drive the grid into the positive voltage zone; consequently, no grid current is drawn.

c. VOLTAGE COMPUTATIONS.

(1) If the signal, e_g, is established at 6 volts peak, then the fixed grid bias can be set at the same figure, or $E_{cc} = -6$ volts. This amount of bias will be just offset by the 6-volt peak of the positive alternation of the signal. This is one extreme of voltage conditions in the input circuit and can be shown numerically as follows:

e_c = signal voltage plus grid bias
$= e_g + E_{cc}$
$e_c = (+6) + (-6) = 0$ volts.

(2) The other extreme occurs at the instant when the peak value of the negative alternation of the signal voltage appears in the grid circuit. At that moment, the signal is —6 volts. With the fixed bias of —6 volts active in the circuit, the instantaneous voltage between the grid and the cathode is the arithmetical sum of the two voltages, or —12 volts. This can be shown numerically as

e_c = signal voltage plus bias voltage
$= e_g + E_{cc}$
$e_c = (-6) + (-6) = -12$ volts.

d. GENERAL.

(1) Between these extremes of grid voltage, the instantaneous voltage between grid and cathode is a function of the instantaneous amplitude and polarity of the signal voltage plus the fixed negative bias. At no time does the control grid become positive.

(2) Another important item is the association between the operating conditions created by the voltages applied and the so-called *operating point* on the dynamic transfer characteristic, illustrated in figure 65, where the load resistor equals 25,000 ohms. This is the same dynamic transfer characteristic developed in A of figure 62 with the static curves omitted. The dynamic transfer characteristic alone is sufficient for a graphical display of the way in which a signal voltage applied to the grid reappears amplified in the plate circuit via the plate current, and also to show the meaning of the operating point and possible conditions of operation. These curves furnish the means for predicting the behavior of the plate current for a signal input.

56. Operating Point

a. QUIESCENT CONDITIONS. To demonstrate the method of predicting the plate-current behavior from the dynamic transfer characteristic, it is necessary first to establish the oper-

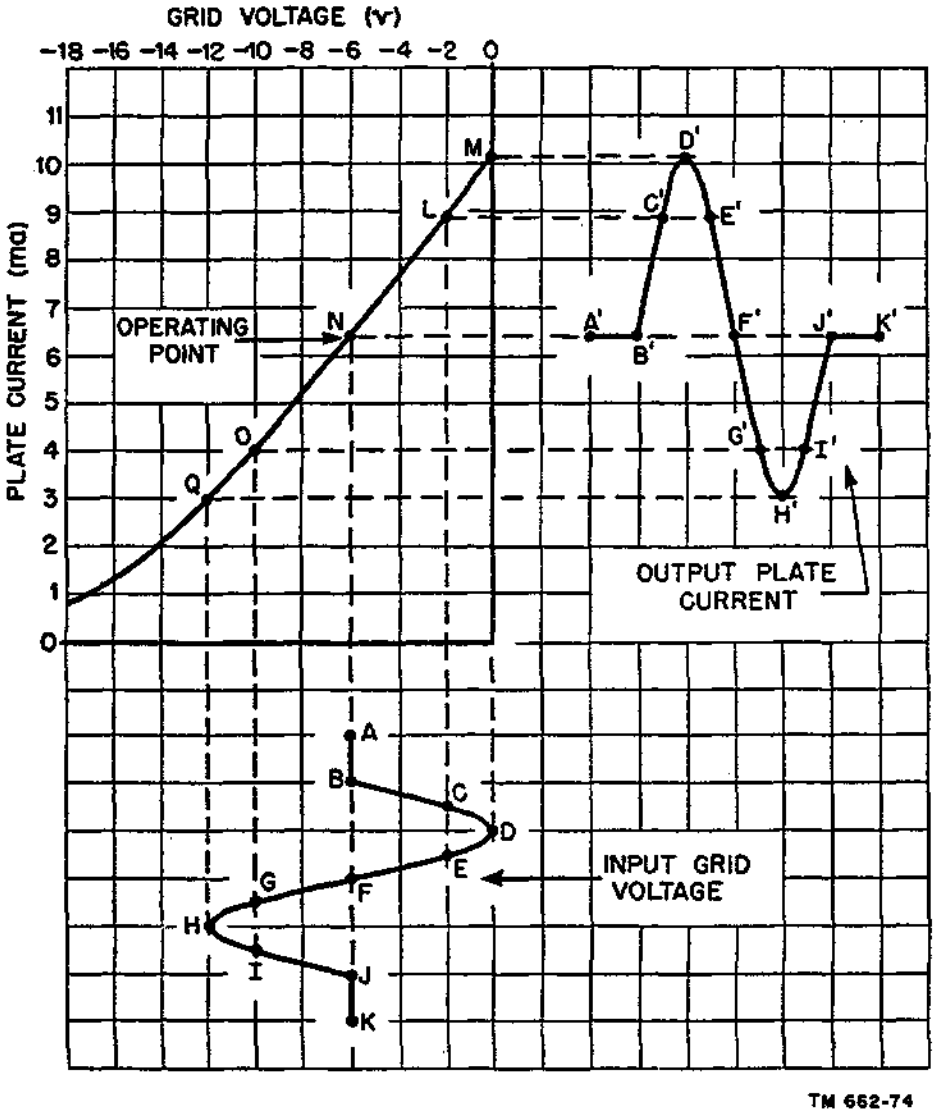


Figure 65. Operating on linear portion of 6J5 dynamic transfer characteristic (R_L equal to 25,000 ohms).

ating point on the characteristic curves. This is set by the amount of fixed grid bias applied to the tube. It establishes a steady value of plate current which prevails for a 0-input signal voltage and is generally referred to as the *quiescent* value of plate current. Based upon the data in figure 64, where a 6-volt peak signal and a —6-volt fixed bias are used, the operating point is N in figure 65. This is seen to equal 6.4 ma and is the quiescent value of plate current.

b. CHOICE OF OPERATING POINTS.

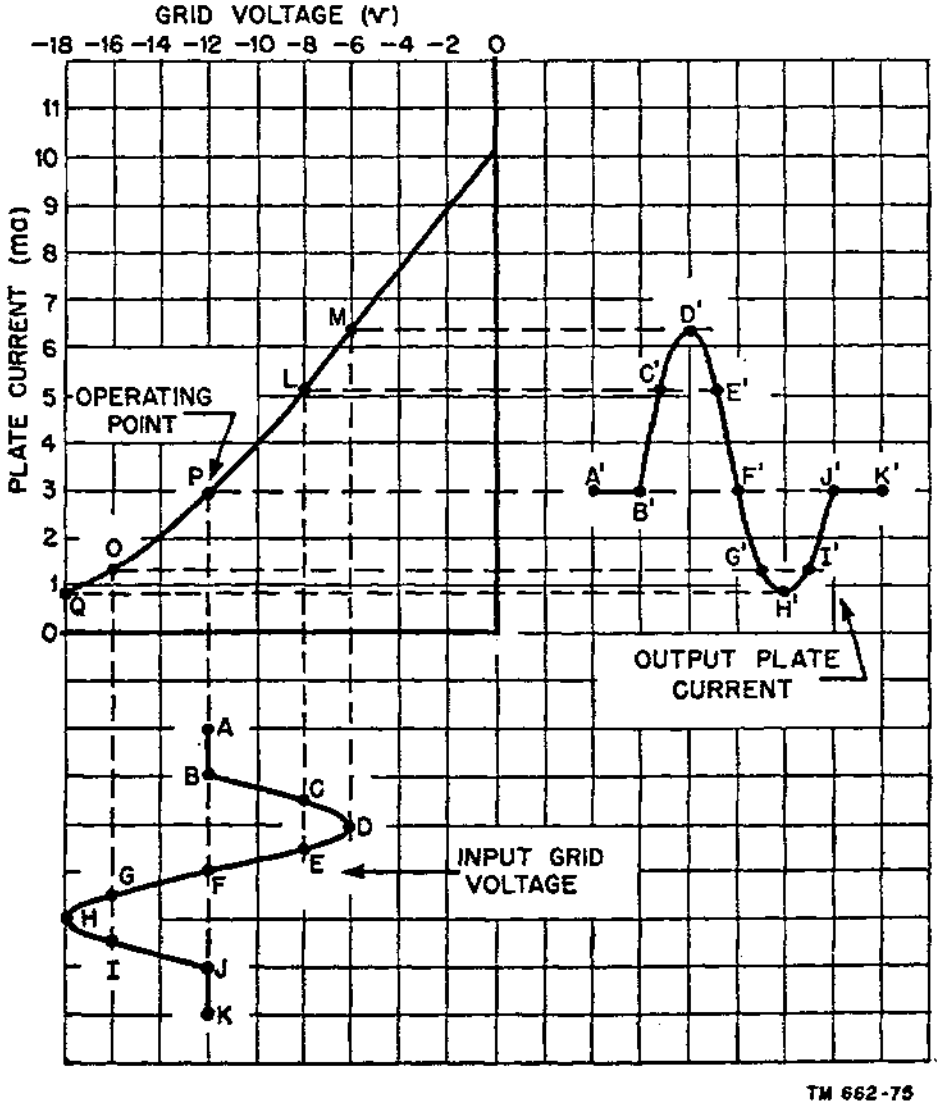
(1) The location of the operating point determines how much change occurs for input signals of different magnitudes. Since it is always desirable to develop a maximum change in plate current for a unit change in grid voltage, the location of the operating point is determined by the maximum amount of signal voltage anticipated in the grid circuit. The reason for this is obvious. Establishing the operating point for a 6-volt peak signal is satisfactory for all signals less than 6 volts peak, but it is not adequate for signals

exceeding 6 volts peak. Such signals will drive the grid positive and cause grid current to flow.

(2) Another factor related to the location of the operating point is the desired behavior of the plate current. Inasmuch as the signal to be amplified is a sine wave, it is necessary for the plate current to rise as much as it falls during the alternate positive and negative half-cycles of the signal. This requirement is described simply by saying that linear changes are required in the plate current. It can be satisfied only by locating the operating point along the linear part of the plate-current curve (N of fig. 65). For instance, selecting the operating point at P (fig. 66) by the application of —12-volt bias permits a 6-volt upward and downward swing in grid voltage, but the change in plate current is nonlinear. The reason will be explained shortly.

c. AMPLIFICATION.

(1) Examples of the plate current result-



e 66. Operating on nonlinear portion of 6J5 dynamic transfer characteristic (R_L equal to 25,000 ohms).

ing from a 6-volt peak signal applied to a simple triode are illustrated in figures 65 and 66. Each graph shows the plate-current results for a different operating point. These correspond to N and P, previously discussed. In each case, the input signal is a sine wave of voltage. The plate-current variations resulting from the applied signal are shown in similar fashion, that is, as graphical representations of a current wave. Faithful amplification of the signal is indicated by similar shapes for the plate-current wave and the input signal-voltage wave. For proper correlation between input signal voltage and output plate current, the same time scale must be used for both. This is accomplished by displaying the cycle of the signal voltage and the plate current along zero axes of similar physical length. Faithful amplification of the input signal is indicated by sine-wave shapes for the plate-current wave, since the input signal voltage in each case is a sine wave. If the plate-current waveshape departs from the original grid sine wave, it is the equivalent of distortion.

(2) The development of the plate-current changes for instantaneous changes in signal voltage requires a point-by-point plot of the instantaneous resultant of the signal and bias voltages on the transfer characteristic. Projections of these plots form the plate-current wave, as accomplished step-by-step in figure 65, where the signal voltage and the developed plate current bear corresponding identifying letters at designated points.

(3) Referring to line AB in figure 65, the input signal-voltage wave is drawn so that its 0-volt point coincides with the fixed bias voltage. This is standard procedure and in this instance coincides with E_{cc} = —6 volts. All other instantaneous amplitudes of the signal then are projected into the characteristic and indicate the instantaneous plate currents. Horizontal projections of these intersections become the instantaneous amplitudes of the plate-current wave.

(4) For instance, line AB is a period during which the signal voltage is 0 (point N), producing the period A'B' wherein the quiescent plate current is 6.4 ma. This is established by the no-signal voltage conditions—that is, the 350-volt supply, the load resistor of 25,000 ohms, and the fixed bias of —6 volts. The signal voltage starts increasing in the positive direction and at point C equals +4 volts. It offsets 4 volts of the negative bias; therefore, the effective grid voltage is —2 volts at this time. A vertical projection from point C on the input signal wave to the characteristic passes through the —2-volt mark on the grid-voltage scale. It intersects the characteristic at L and equals 8.9 ma. A horizontal projection on the plate-current wave scale produces the point C'.

(5) The peak of the input signal labeled D has a voltage magnitude of +6 volts. The effective grid voltage, therefore, equals 0 and the projection on the characteristic produces point M and equals 10.5 ma. Projecting this point horizontally on the plate-current timebase produces the peak amplitude D'. Point G is projected to produce point O; point H is projected to produce point Q. Treatment of every other point on the signal-voltage wave in similar fashion develops the plate-current waveshape of figure 65.

d. ANALYSIS OF ILLUSTRATIONS.

(1) An analysis of the graphical display of the signal voltage, dynamic transfer characteristic, and resultant plate-current waves affords pertinent information. A casual inspection of the signal-input and plate-current waves discloses a substantial similarity, which signifies relatively little distortion. A more critical examination shows that the positive alternation of the plate current has a

slightly higher peak amplitude than the negative alternation. Nonlinearity of this kind is a form of distortion, but in this case it is not too great. Even this small amount of distortion can be eliminated by increasing the load resistance, reducing the signal voltage, and operating entirely along the straight part of the characteristic.

(2) An aggravated example of distortion appears in figure 66. It results from the choice of the operating point on the dynamic transfer characteristic relative to the swing in grid voltage caused by the signal. The plate-current wave is developed as shown in figure 65, but the steps have been omitted, although corresponding parts of the signal and plate-current waves are labeled similarly.

(3) The nonuniformity in plate-current changes on both sides of the quiescent value is evident in the plate-current wave of figure 66. The curvature in the dynamic transfer characteristic for relatively high values of grid bias results in *flattening* of the peak of the negative alternation. This is serious distortion when the intended function of the triode amplifier is distortionless amplification of a sine wave. It can be said in passing that wave flattening of this kind is the equivalent of introducing frequencies which were not present in the single-frequency input signal.

(4) The statements in the preceding paragraphs are a brief treatment of the subject of amplification. More elaborate and complete details are contained in chapter 6. In the meantime, it should be noted that the amplitude of the plate-current curves in figures 65 and 66 relative to the pictured amplitudes of the input signals is not an indication of the amount of amplification being obtained. This can be derived only from calculation (or measurement) of the voltage drop developed across the triode load by the changing plate current and comparison with the amplitude of the input signal.

e. GENERAL. Concerning the types of distortion that can be developed in an electron-tube amplifier, they are more numerous than the two examples illustrated in figures 65 and 66. Additional examples are given later in this manual.

57. Interelectrode Capacitances

a. An important electrical effect is associated with triode tubes. It is the capacitance presented by the facing metal surfaces which are the tube electrodes. Capacitance exists between the cathode and the control grid, between the cathode and the plate, and between the control grid and the plate.

b. The interelectrode capacitance between the control grid and the cathode bears the label C_{gk}, the subscripts indicating the tube electrodes which form the tiny capacitor. The capacitance between the control grid and plate is labeled C_{gp}, and between plate and cathode C_{pk}. These capacitors are illustrated in figure 67. These capacitances are relatively small, being possibly 2 to 10 $\mu\mu$f. Nevertheless, they are very important and cannot be ignored in some cases.

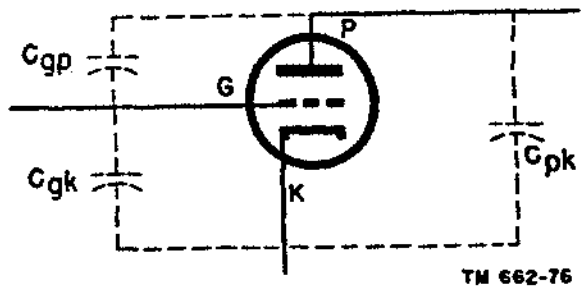


Figure 67. Location of interelectrode capacitances within triode.

c. The triode is used in many circuits that involve the phenomenon of resonance. The capacitance between the triode electrodes such as C_{gk} and C_{gp} is additive to any already there as a part of the resonant systems connected between these electrodes. Consequently, substitution of one tube for another is capable of impairing the condition of resonance because of changes in tube capacitance.

d. In all applications of the triode and other multielectrode tubes, a form of circuit isolation is attained between the circuit components which form the control-grid circuit and those which are connected to the plate circuit of the tube. Under ideal conditions, the only coupling between the control-grid and plate circuits is the stream of electrons inside the tube. The presence of capacitance inside the tube between the control-grid and plate electrodes tends to defeat the usefulness of the triode as a means of attaining circuit isolation. The interelectrode capacitance between the control-grid and plate circuits acts as a path by which energy present in the plate circuit is transferred back to the grid circuit. The result is interaction between the control-grid and plate circuits. This can be serious when the grid circuit and the plate circuit of the triode contain systems which are resonant to the same or approximately the same frequency. This action is called *feedback*. The higher the frequency of operation the worse is the situation, since the reactances of C_{gk} and C_{gp} become negligible and increase the feedback effect.

e. The results of uncontrolled feedback are bad. The circuit behaves as a very unstable amplifier. If the feedback is excessive, the system becomes useless as an amplifier; instead, it generates a signal of its own. This action is called *oscillation*. In order to minimize the tendency toward oscillation and so permit the triode to function as an amplifier, recourse is made to a circuit action known as neutralization, which will be discussed later. In neutralization, the interelectrode capacitance between the control grid and the plate is neutralized by means of a special capacitor located outside the tube and connected between the grid and plate circuits.

f. Freedom from uncontrolled feedback in amplifiers can be attained by use of electron tubes which contain more than three—sometimes four or five—electrodes. These *tetrodes* and *pentodes* are discussed fully in the following chapter.

58. Summary

a. Control grids, as used in triodes, are composed of such metals as molybdenum, nichrome, iron, and an alloy of nickel and iron.

b. The inside view of a glass triode is obscured by the opaque coating formed by a *getter*. The purpose of the getter is to absorb any gases that are initially liberated from the electrodes during operation.

c. The purpose of the control grid in triodes is to govern the movement of electrons from the space charge to the plate.

d. One distinguishing feature of the triode is that its plate current can be cut off despite the presence of a positive d-c voltage on the plate.

e. Amplification occurs in a triode when it delivers a stronger signal to the output circuit than it receives.

f. D-c power sources for a triode consist of an A-battery, which supplies the filament voltage; a B-battery, which supplies the plate voltage; and a C-battery, which supplies the control-grid voltage.

g. Operating potentials of a triode are the fixed d-c operating voltages of the filament, control grid, and plate.

h. The reference point of the triode usually is the cathode (or the common junction point of the voltage sources) and it usually is grounded.

i. An electrostatic field exists between the cathode (space charge) and the control grid in a triode. The direction of this field is such as to pull electrons to the plate when the grid is made positive. The reverse is true when it is negative.

j. Grid current is a condition that prevails in a triode that exists when electrons attach themselves to the control grid and complete a path to it. It is negligible when the grid is at zero or negative potential and is more predominant as the grid is made more and more positive.

k. Placing a voltage on the control grid sets up two electrostatic fields, one between cathode and control grid and the other from control grid to plate. The direction of these fields is dependent on the polarity of the voltages applied to the electrodes.

l. A low voltage applied to the control grid can exert on the space-charge electrons as much influence as (or even more than) a very much higher voltage applied to the plate.

m. When the potential on the control grid is such that it completely stops the movement

of electrons through a tube, the tube is said to be *cut off*.

n. When the potential on the control grid is positive, it aids the plate by pulling more electrons to it because more electrons pass through the grid openings.

o. In some tubes, a grid-voltage change of a few volts can have the same effect on plate current as changing the plate voltage by 10, 20, or even 50 volts. (In some instances, the effect can be less and in others more.)

p. When the maximum and minimum points of one waveshape occur at the same instant as the maximum and minimum of another waveshape, it is said that the two waveshapes are *in phase.*

q. The plate current of a triode always remains unidirectional even though it may vary above and below a reference level.

r. The polarity of the plate (with reference to the cathode) in a triode always remains positive.

s. The control-grid voltage can change very slowly or very rapidly and the plate voltage varies accordingly.

t. In most cases, the presence of grid current is undesirable because it represents a consumption of power.

u. Bias can be defined as the d-c voltage existing between the grid and cathode of a triode.

v. Characteristic curves display the behavior of electron tubes easily and specifically.

w. In the plate-current grid-voltage characteristics, the grid voltage is made variable (causing changes in plate current) and the plate voltage is made constant. In the plate-current plate-voltage characteristics, the plate voltage is made variable (also causing changes in plate current) and the grid voltage is made constant.

x. Static characteristics are curves that indicate tube behavior when the voltages applied to its electrodes are determined by voltage sources E_{bb} and E_{cc}.

y. Plate-current saturation is reached when no further increase in plate current occurs as the grid is made more positive.

z. In general, grid-family and plate-family curves furnish the same information. The grid family displays the plate current for small increments of grid-voltage change and substantial fixed differences in plate voltage; the plate family displays the effects of small increments of plate-voltage change and larger fixed increments of grid-voltage change.

aa. The plate current corresponding to a fixed change in grid voltage is a function of the *operating region* on the plate-current curve. The *operating point* determines the linearity and nonlinearity of the output waveshape of a triode.

ab. The tube *constants* are:

$$\text{Amplification factor } (\mu) = \frac{\triangle e_b}{\triangle e_c} (i_p \text{ constant})$$

$$\text{Transconductance } (g_m) = \frac{\triangle i_b}{\triangle e_c} (e_b \text{ constant})$$

$$\text{A-c plate resistance } (r_p) = \frac{\triangle e_b}{\triangle i_b} (e_c \text{ constant}).$$

ac. Triodes generally are classified as low-μ (μ is less than 10), medium-μ (μ is between 10 and 30), and high-μ (μ is 100 or more).

ad. R_p is defined as the d-c internal resistance of a tube when steady values of voltage are applied to its electrodes. The term r_p is defined as the a-c internal resistance of a tube when varying values of voltage are applied to its electrodes.

ae. The higher the applied plate voltage (or the lower the negative grid voltage), the lower is the a-c plate resistance.

af. When comparing μ, g_m, and r_p, μ remains relatively constant under virtually all conditions. The value of r_p varies greatly at high values of negative grid bias or low plate voltage. G_m varies oppositely to r_p.

ag. The tube constants are a means of comparing tubes of a similar type and permit the selection of a tube to fit specific needs.

ah. The dynamic characteristics of a tube can be described as a graphic portrayal of tube behavior under *load.*

ai. When a signal source and a load are used, the following mathematical relationships hold true:

$e_c = E_{cc} + eg$; $eb = E_{bb} - i_b R_L$; $e_{RL} = i_b R_L$.

aj. A load line displays the way in which the output of the plate-supply voltage is distrib-

uted between the load and the internal resistance of the tube under different conditions of plate current.

ak. The dynamic transfer characteristic curve correlates the plate-current grid-voltage relationship with the load present in the circuit.

al. The total change in plate voltage always is equal to the change in voltage across the load.

am. Nonlinearity in electron-tube behavior is a source of distortion and is highly undesirable.

an. If a triode amplifier is to operate without grid current, the amount of fixed negative bias must be at least equal to the peak value of the positive half of the input grid signal.

ao. The plate current in a triode amplifier is said to be *quiescent* when no signal is applied to its input circuit.

ap. The interelectrode capacitances of a triode, C_{gp}, C_{pk}, and C_{gk}, are in the order of 2 to 10 $\mu\mu$f.

aq. The effect of interelectrode capacitance can lead to feedback and oscillation.

59. Review Questions

a. Name some metals that are used to manufacture control grids in triodes.

b. What famous person inserted the *third element* into the diode?

c. Why are the elements of triodes generally larger in transmitters than in receivers?

d. What substances are used as *getters* in triodes?

e. Why are getters necessary in triodes?

f. What is the electrical difference between a diode and a triode?

g. Is it possible for the control grid to overcome the influence of a very high plate voltage in the order of a few thousand volts? Why?

h. Why is the control grid in a triode sometimes compared to a *valve*?

i. Comparatively speaking, what are the approximate voltage differences between the A, B, and C supplies in a triode?

j. Are the polarities of B- and C-batteries the same for all triodes?

k. What is meant by the operating potentials of a triode?

l. What point usually is grounded in a triode circuit?

m. In physical construction, why is the control grid placed closer to the cathode than to the plate?

n. What influence does the electrostatic field existing in a triode have on the electron flow through the tube?

o. Will grid current flow when the control grid is at zero potential?

p. Explain the differences in direction of the electrostatic fields in a triode when the grid is positive and negative.

q. What is meant by *cut-off* in an electron tube?

r. Upon what factors does the cut-off voltage of an electron tube depend?

s. Name the effects that exist in making the control grid positive in a triode.

t. What is meant when two voltages are said to be *in phase*?

u. Can the plate voltage of a triode ever go negative? Why?

v. Does the plate current have the same shape as the control-grid voltage in a triode?

w. Why is a negative control grid desired in the majority of cases?

x. Define bias, grid voltage, and cathode voltage.

y. What is the main purpose of characteristic curves?

z. What is meant by the notations E_{bb}, i_b, I_b, e_c, and E_b?

aa. What are the dependent and independent variables in both the plate-current grid-voltage and plate-current plate-voltage characteristics?

ab. What are the differences between static and dynamic characteristic curves?

ac. Why is plate current reduced when the control grid is made *too* positive?

ad. What are the advantages and disadvantages of using oxide-coated emitters?

ae. Why are grid-family characteristic curves used instead of a single characteristic curve?

af. Define μ, g_m and r_p.

ag. What is the differencee between R_p and r_p?

ah. What is meant by a variable-μ tube?

ai. How does r_p vary with the plate-supply voltage? Grid-supply voltage?

aj. What is the mathematical relationship between μ, g_m, and r_p?

ak. Is the change in plate current for a change in grid voltage more or less when a load is used in a triode circuit? Why?

al. Explain what a dynamic transfer characteristic curve is.

am. How would you go about drawing a load line for a given set of grid-family curves?

an. Why does nonlinearity of characteristic curves cause distortion? How can it be minimized?

ao. What three voltages are present in the control grid-cathode circuit of a triode amplifier?

ap. When can a quiescent value of plate current be obtained?

aq. What is the approximate value of interelectrode capacitance existing between the electrodes of a triode tube?

ar. Is interelectrode capacitance more noticeable at higher or lower frequencies? Why?

as. Why is *neutralization* used in some triode amplifiers?

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

EXTRACT

Paragraphs 60—74

United States Government Printing Office
Washington: 1952

AGO 2244A

CHAPTER 5

MULTIELECTRODE TUBES

Section I. TETRODES

60. General

a. Although the triode is an important device in communications, its use in amplifying systems is limited in some respects. The principal reason is the interelectrode capacitance between its electrodes, especially the capacitance between the control grid and the plate. As the frequency of operation is increased, the grid-plate capacitance affords an easier path for the transfer of energy back from the output to the input circuit. This action is most pronounced in a resonant system in which the grid and plate circuits are tuned to the same or similar frequencies. The result is that triode tubes seldom are used as amplifiers without recourse to special neutralizing systems to counterbalance the undesired feedback.

b. Neutralization is not wholly satisfactory. The higher the frequency of operation, the more critical is the adjustment. Sometimes it is impossible to neutralize properly over the entire band. Above all, neutralization is a critical adjustment and, frequently, a bothersome one. It still is used in some equipment, but in general its use has been reduced by the development of new tube types which obviate the necessity for neutralization by greatly reducing the interelectrode grid-plate capacitance as a feedback path.

c. In addition to the problems of feedback, the triode does not satisfy all the amplifying needs encountered in receivers, transmitters, and related apparatus. The physical relationship between the electrodes of the triode is such as to set unsatisfactory limits on the degree of amplification that can be achieved in a practical tube. At one time this posed a serious problem for design engineers because progress in communication depended on increasing the amplifying capabilities of equipment.

d. Today the answer is found in two types of tubes. Both are based on the triode but represent modifications of the original three-element electron tube. One of the versions is the *tetrode,* or four-electrode electron tube, which contains an electron emitter, two grids, and a plate. The other is the *pentode,* which contains five electrodes: an electron emitter, three grids, and a plate.

e. The development of electron tubes since the early 1920's has resulted in more than just the multielectrode tetrode and pentode. Other tubes which have been developed are various combinations of diodes, triodes, tetrodes, and pentodes in the same envelope. These are identified by the general name of *multiunit* tubes.

61. Tetrode

a. SCREEN GRID. The four-electrode tube contains all the electrodes of the triode (with generally similar functions), and in addition a fourth electrode. This is the *screen grid.* As a rule, the four-electrode tube is called a tetrode, although upon occasion it is referred to as a screen-grid tube.

b. PHYSICAL CONSTRUCTION.

(1) The physical organization of the tetrode (fig. 68) does not differ too much from that of the triode. In A, the screen grid of the tetrode (type 48) is rectangular in shape. The plate is fin-shaped for heat dissipation purposes. In B, the outer screen grid is a perforated-metal structure

of circular shape (type 32), located between the glass envelope and the plate electrode. The inner screen grid is oval and is located between the control grid and plate. There is variation in the shape of the grids; in some instances a helical form is used. The functioning of the electrodes is fundamentally the same regardless of the shape.

to the base are called *double-ended* tubes. If *all* the electrodes appear as pins or prongs in the base of the tube, they are called *single-ended* tubes. In some tetrodes designed for use in receivers and similar low-power equipment, the cap illustrated in C affords electrical connection to the control grid. The plate, screen-grid, and heater (or filament) junc-

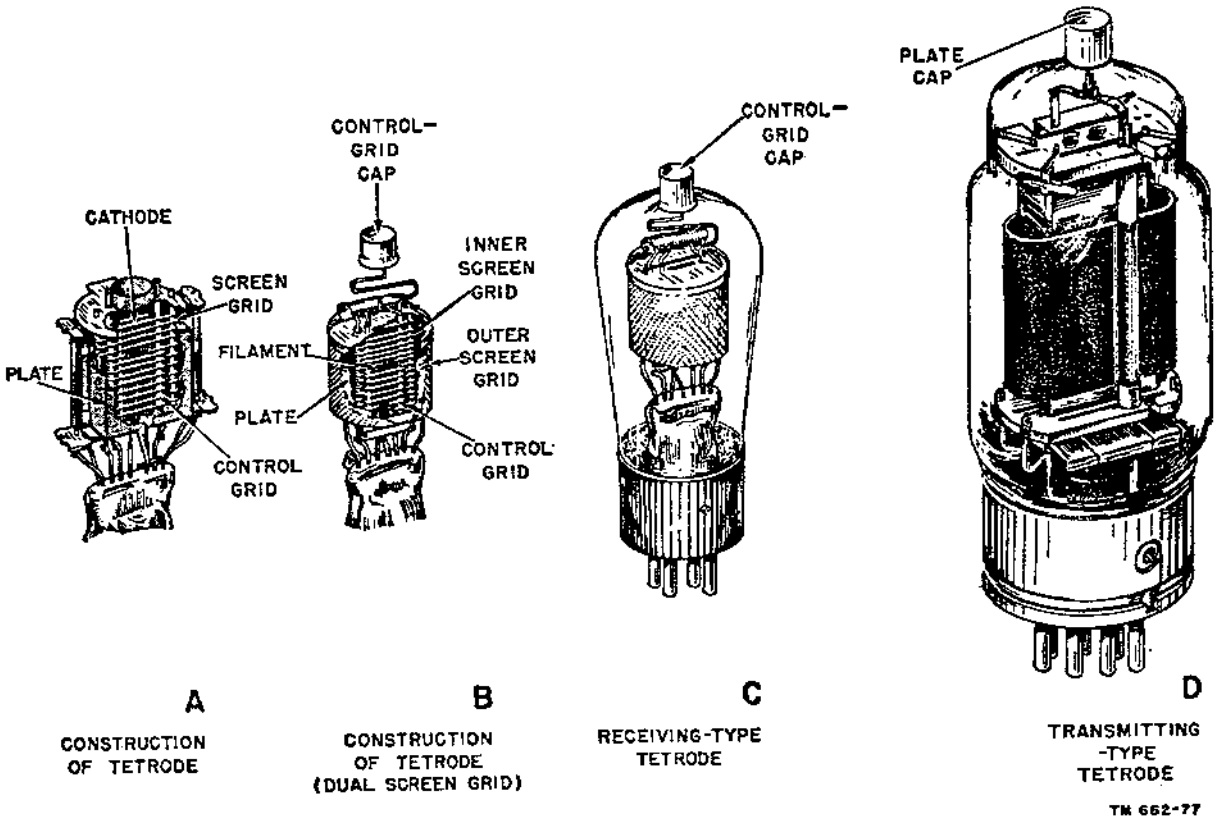


Figure 68. Physical construction of tetrodes.

(2) C and D show external views of two tetrodes. The tubes are substantially alike in appearance, but differ in one respect. The practice of using pins in the tube base as connecting points to the electrodes inside the envelope is followed in the tetrode, but an exception is the use of a metal connecting cap on the top of the tube. Tubes which have electrodes connected to portions of the envelope in addition

tions are made through the tube base pins. In some higher-power tubes, such as are used in transmitters, the cap furnishes electrical contact with the plate electrode, as in D. The remaining tube electrodes terminate at the base pins. The reason for cap connections to the control grid or to the plate, as the case may be, is the desire to reduce the capacitance between the connecting pin termina-

tions of the control grid and the plate.

c. TETRODE CIRCUIT. It is common practice to use the full names, such as control grid and screen grid, but for tube schematics it is advantageous to designate these electrodes in abbreviated form as G1 and G2. The smaller number is assigned to the grid which is closer to the cathode, this being the control grid. Therefore, G2 represents the screen grid. These notations are included in two schematic representations (fig. 69). The old tube symbol, in A, finds occasional use in modern literature, and therefore, is shown here. B shows the modern tube symbol. It also is interesting to note that abridgement of the words *screen grid* to the single word *screen*, as meaning the same thing, is practiced regularly. When illustrated schematically with operating voltages applied to all the electrodes, the tetrode appears as in figure 70. The main difference between the tetrode and the triode is the screen circuit and the source of its operating voltage. In normal use the screen is made positive relative to the cathode by receiving a voltage from source E_{bb}, which also supplies the plate voltage. In the majority of instances, the d-c screen voltage is appreciably less than the d-c plate voltage.

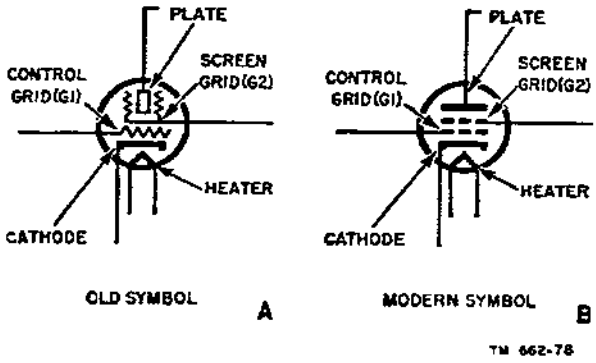


Figure 69. Tube symbols for tetrode.

d. ANALYSIS OF CIRCUIT.

(1) The organization of the tetrode circuit relative to signal transfer (fig. 70) is the same as that of the triode. The control-grid-to-cathode circuit is the *input* part of the tube system (including e_g and E_{cc}), and the plate-to-ground circuit is the *output* part of the tube system (including e_b and E_{bb}). The circuity between the emitter and the common junction point, shown grounded, is the *cathode* circuit. This, too, conforms with the breakdown of the triode.

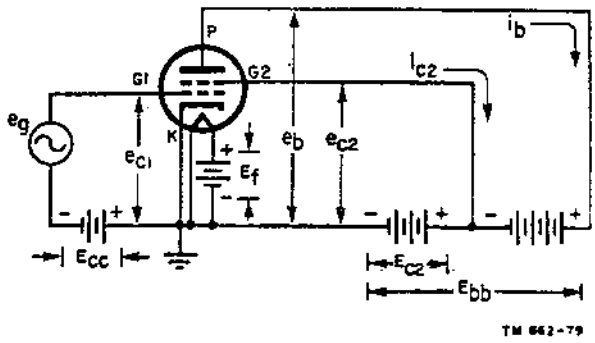


Figure 70. Circuit representation of tetrode.

(2) The presence of the screen electrode introduces new voltage and current notations. The voltage between the control grid and the cathode bears association with G1, and is, therefore, identified as e_{c1}. On the other hand, the screen-grid voltage source is a part of E_{bb}, but the voltage applied to the screen electrode is identified apart from the plate voltage. Being related to G2, it bears the notation e_{c2}, and its portion of E_{bb} is labeled E_{c2}.

(3) The current label i_{c2} identifies the screen-grid current. The screen is located in the space between the control grid and the plate, and therefore, it is in the path of the electrons flowing through the tube. Since it is subjected to a positive voltage, it does more than just accelerate electrons toward itself and the plate. It attracts some of the electrons, which comprise the screen current. Again, the current notation is seen to bear an association with the subscript letter *c* which is used with all electrodes identified as grids. The screen current usually is much smaller than the plate current.

e. FUNCTION OF SCREEN GRID.

(1) The main purpose of the screen-grid electrode is to reduce the plate-to-grid capacitance, which is a path for feed-

back in high-frequency amplifiers. Feedback may lead to self-oscillation of the amplifier, which is undesirable. With an average of about 2 $\mu\mu$f grid-plate capacitance in a triode, this value is reduced to approximately .01 $\mu\mu$f or less in a tetrode. The screen-grid accomplishes this by acting as an electrostatic shield between the control grid and the plate, consequently reducing the grid-plate capacitance. When an outer screen-grid is used, it serves to isolate the plate of the tube from the external circuit.

(2) The screen current, i_{c2}, that flows as a result of E_{c2} performs no useful purpose. Most of the emitted electrons from the cathode flow to the plate through the openings in the screen-grid mesh. Consequently, the screen reinforces the action of the plate by helping it to attract more electrons to the plate. At the same time, the screen has another effect; it makes the plate current practically independent of plate voltage because of its shielding action. Inasmuch as the screen is between the control grid and the plate, changes in the value of the voltage on the plate have little effect on the space charge. As a matter of fact, it is possible to view the plate-voltage field as terminating on the screen. This does not imply that the plate voltage is unimportant. It accounts for the advance of electrons to it and the plate circuit is still the output circuit. However, the attracting force responsible for the movement of electrons beyond the confines of the control grid is the voltage on the screen rather than the voltage on the plate.

62. Plate-current Plate-voltage Characteristic Curves

a. The behavior of a tetrode under various conditions can be analyzed from its plate-current plate-voltage characteristic curves (figs. 78 and 71, with e_g excluded) as was done in the analysis of the triode. The now obsolete UY–224 tetrode was used to obtain the curves illustrated because it exhibits certain properties of fundamental interest which later types of tetrodes do not show equally well. Figure 71 shows curves for only one control-grid and screen-grid voltage setting. Since e_g is not introduced in the circuit the control-grid voltage, e_{c1} or E_{c1}, is held constant at —1.5 volts and the screen-grid voltage, E_{c2}, is held constant at +75 volts. The filament voltage, E_f, is a d-c voltage of 2.5 volts.

b. Referring to figure 71, curve i_b is the plate current and curve i_{c2} is the screen current (Y axis) for the stipulated changes in plate voltage (X-axis). It can be seen that great changes occur in these two curves below a certain value of plate voltage, that is, from E_{bb} values of 0 to about 90 volts. It is in this region that great interest lies, although the operating range of the two curves, when used for amplifier design, is substantially above the 90-volt value. Curves i_b and i_{c2} are added to produce curve $i_b + i_{c2}$. This illustrates that changes in plate voltage E_{bb} do not appreciably affect the total current through the tetrode.

c. The previous statement that the plate current is not affected too much by changes in plate voltage in a tetrode appears to be contradicted in an examination of the curves. This is because, with voltage applied to the plate and +75 volts to the screen, an electrostatic field exists between the screen and the cathode and not between the cathode and plate (cathode is at 0 potential). This field attracts electrons to the screen grid and a small screen current (4 milliamperes) flows in the external screen circuit. Some electrons do reach the plate, however, as evidenced by the flow of a very small plate current (.5 milliampere) at 0 plate voltage.

d. Raising the plate voltage from 0 to +2 volts causes an increase in plate current and a decrease in screen current. This is indicated by the upward slope in the plate-current characteristic and the downward slope of the screen-current characteristic. Note that as the plate voltage is increased to +5 volts and slightly higher, the plate-current curve slopes downward and continues so for an appreciable distance. This appears to be the contrary of what

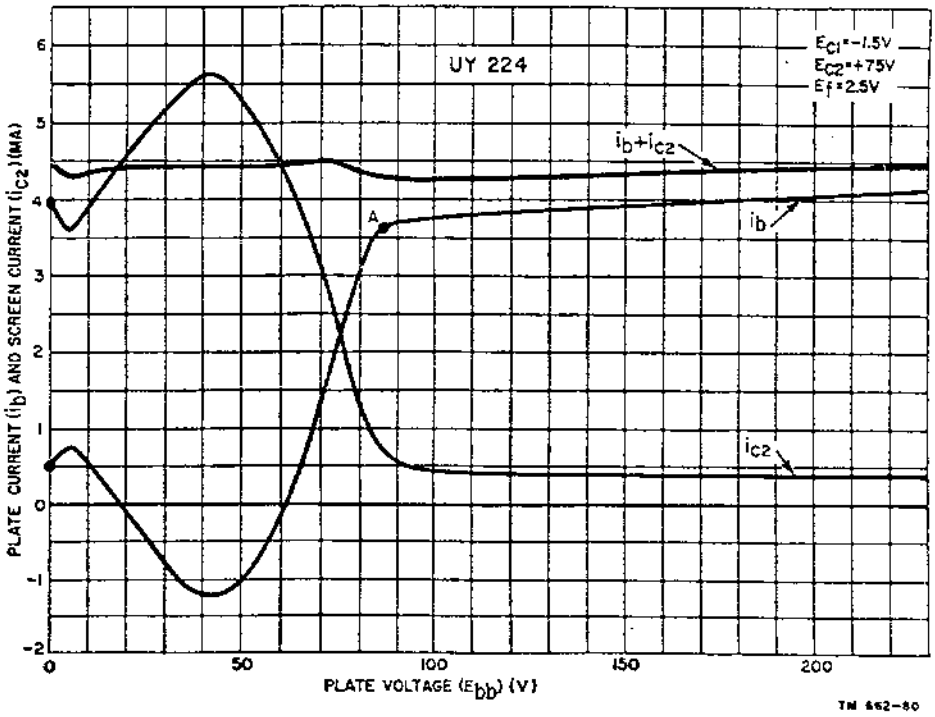


Figure 71. Plate-current plate-voltage characteristic curve for UY–224 tetrode.

should happen. By ordinary tube behavior the plate current should increase rather than decrease as the plate voltage increases. The decrease is caused by a phenomenon known as *secondary emission.*

e. Secondary emission occurs when electrons from the space charge strike the plate with sufficient force to dislodge electrons from the plate material itself. These dislodged electrons are known as *secondary* electrons. With the screen voltage fixed, the velocity with which the space-charge electrons (known as *primary* electrons) arrive at the plate increases as the plate voltage increases. At low plate voltages, secondary electrons dislodged from the plate under primary electron bombardment are attracted to the higher-potential screen. The movement of these secondary electrons is in the direction *opposite* to the regular flow of electrons from cathode to plate. The result of this dual-directional current flow is that the current in the plate circuit decreases as more and more secondary electrons are dislodged from the plate. These secondary electrons are attracted to the screen and the screen current increases. The decrease in plate current and increase in screen current resulting from secondary emission are represented by the curves in figure 71. The plate current, therefore, continues to decrease as the screen current increases. When the plate voltage is increased and approaches the screen potential of +75 volts, some of the secondary electrons are attracted back to the plate, causing the plate current curve to turn in an upward direction. When the plate voltage reaches the screen voltage, the plate field is now strong enough to prevent the secondary electrons from leaving the vicinity of the plate because they are nearer to the plate than they are to the screen.

f. As the plate voltage exceeds the screen voltage, most of the electrons which pass through the screen openings arrive at the plate. This condition represents the relatively flat portion of the i_b curve (beyond $E_{bb} = 90$ volts). Increasing the plate voltage beyond 90 volts does not cause an appreciable increase in plate current, because the increased attracting force caused by the higher positive voltage on the plate does not affect the space charge as much

as the screen does; therefore, its action on the space-charge electrons is negligible.

g. Normal operation of a tetrode as a distortionless amplifier is in the zone where the plate current curve i_b is not subject to radical fluctuations caused by secondary emission effects, to the right of point A.

h. In the plate family of characteristics for the more modern 24A tetrode (fig. 72), the control-grid voltage is varied from 0 volts to —6 volts in steps of 1.5 volt; the screen-grid voltage, E_{c2}, is held constant at +90 volts and the plate voltage is varied over a wide range, from 0 volt to +500 volts. Several significant differences can be observed in figures 71 and 72.

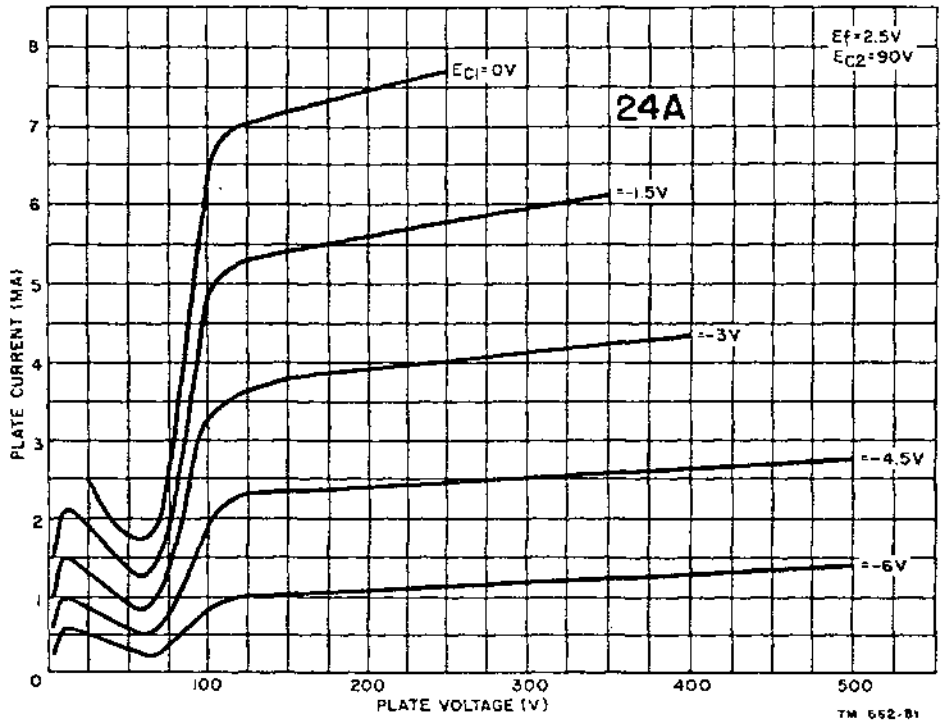


Figure 72. Plate family of characteristic curves for 24A tetrode.

i. It is to be noted that none of the characteristic curves for the modern 24A drop below the 0 value of plate current, as they do for the obsolete UY–224. This does not mean that the modern tetrode is free from negative resistance effects, for, as can be seen, the plate current does decrease with increasing plate voltage over the region where E_{bb} is approximately 0 to 70 volts. It is simply that the extent of the negative resistance effect is not as great.

j. This improvement is attributable to the kind of material used for the plate. The plate of the 24A tetrode is treated chemically so that fewer secondary electrons are dislodged by the primary electrons. This reduces the number of secondary electrons that are available to be attracted to the screen when its voltage exceeds that of the plate.

k. As to the limitations of its use, the modern tetrode is subject to secondary emission also, although it performs as a somewhat better amplifier than the old-type tetrode.

63. Constants of Tetrodes

a. GENERAL. Like the triode, the tetrode is identified with three basic tube constants: a-c plate resistance r_p, amplication factor, μ, and transconductance g_m. The meaning of each is the same as when they are used for the triode, although the different organization of the tetrode establishes a contrasting range of values for these constants.

b. A-C PLATE RESISTANCE. The a-c plate resistance of the tetrode is very high in compari-

son with that of the triode. The reason for this is the action of the screen grid; it reduces very substantially the effect of a change in plate voltage on the plate current. The a-c plate resistance of the few receiving-type (low-power) tetrodes averages about 400,000 to 500,000 ohms, although in the receiving-type power tetrodes it is much lower—approximately 70,000 to 100,000 ohms. High-power tetrodes used in transmitters display much lower values of plate resistance, usually about 6,000 to 10,000 ohms.

c. AMPLIFICATION FACTOR. The amplification factor of tetrodes is many times higher than in triodes. In contrast to triodes, which possess μ values of from about 5 to perhaps 50, low-power tetrodes are rated at from about 400 to perhaps 600. High-power tetrodes used in transmitters have μ values approximating 160.

d. TRANSCONDUCTANCE. The transconductance is not too high in tetrodes, despite the high μ rating. The reason for this can be explained by the equation $g_m = \mu/r_p$. The value of r_p, in the denominator, increases to a greater proportion than μ, in the numerator, does in a tetrode. Therefore, the ratio of μ/r_p decreases in proportion and consequently g_m decreases. In general, the g_m of low-power tetrodes is about 1,000 to 1,500 micromhos; special power types average between 4,000 and 4,500 micromhos.

64. Advantages and Disadvantages of Tetrode

a. ADVANTAGES. The advantages of the ordinary tetrode are relatively few. It does reduce the capacitance between plate and control grid, and therefore the amount of feedback. Also, it affords greater amplification than is available with a triode. These are the background items which explain its use as an amplifier in a number of communication receivers. However, it is necessary to understand that the receiver and other similar equipments which utilize the low-power tetrode are not the most modern devices. Present-day apparatus generally uses the pentode, which is an elaboration created to overcome the disadvantages of the tetrode.

b. DISADVANTAGES.

(1) The disadvantages of the tetrode outnumber the advantages. As stated previously, it is limited to a portion of the over-all plate-current characteristic. Only in this zone, where the plate voltage exceeds the screen voltage, are secondary emission effects negligible. In view of the effects of the plate load on the plate voltage when a signal voltage is applied to the control grid, the use of a very high value of plate-supply voltage, E_{bb} is warranted. Only then can the required swing in plate voltage take place and still have the lowest value of plate voltage, e_b, exceed the applied screen voltage. Under such conditions the tetrode functions as a linear amplifier. However, if the plate-supply voltage is insufficient and causes the effective voltage at the plate momentarily to be less than the screen voltage, secondary emission occurs, with consequent impairment of the performance of the amplifier. Excessive distortion is the result.

(2) The necessity for a very high plate-supply voltage, E_{bb}, to assure that e_b always exceeds, or at least never goes below E_{c2}, may be inconvenient. Moreover, the fulfillment of the voltage requirements at the plate and at the screen introduces a limitation on the amount of signal, e_g, that can be fed to the input circuit of the tube. The changes in plate current must be kept to a reasonable minimum in order that the drop across the load resistor never makes e_b less than E_{c2}. This limits the tetrode to the handling of relatively weak signals.

c. GENERAL. The fact remains that few receiving-type tetrodes are manufactured today. For all practical purposes they can be considered obsolete. This is not true, however, of transmitting-type tetrodes. Many communication needs demand high amplification, relatively low plate-supply voltages, and the handling of substantial amounts of power. These are accomplished by means of the *pentode* and the *beam power tetrode.*

Section II. PENTODES

65. Physical Construction

a. The *pentode* is a five-electrode electron tube. It contains an emitter, three grids, and a plate. The grid closest to the cathode, G1, is the control grid; next is the screen grid, G2, and the third, located between the screen grid and the plate, is the new *suppressor grid,* G3. The construction of a metal-type pentode is shown in A of figure 73; symbolized, the pentode is shown in B.

c. In external appearance some pentodes resemble the tetrode. This similarity is so great, even to the use of control-grid or plate caps on the top of the tube envelope, that identification by visual inspection is difficult. Three receiving-type pentodes are shown in figure 74. The envelope of a pentode may be glass, as in A, or metal. A departure from the tetrode appear-

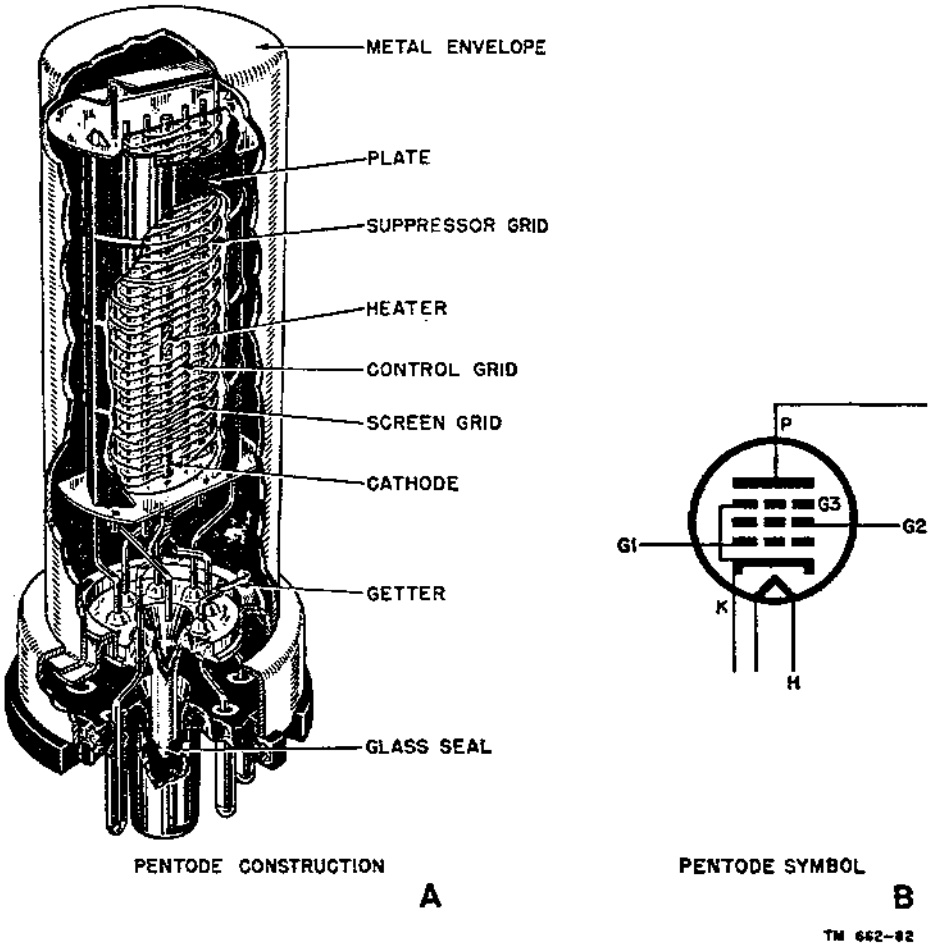


Figure 73. Physical construction (metal-type) and symbol of pentode.

b. Functionally speaking, the action of the emitter, control grid, screen grid, and plate in the pentode are the same as in the tetrode, excepting that, whereas the tetrode suffers from negative resistance effects, the pentode is free from these because of the action of the suppressor grid.

ance is the acorn-type tube shown in B. This is a comparatively small tube requiring a special socket and having wire extensions serving as the tube pins. Another physical feature of the acorn pentode is the location of the plate

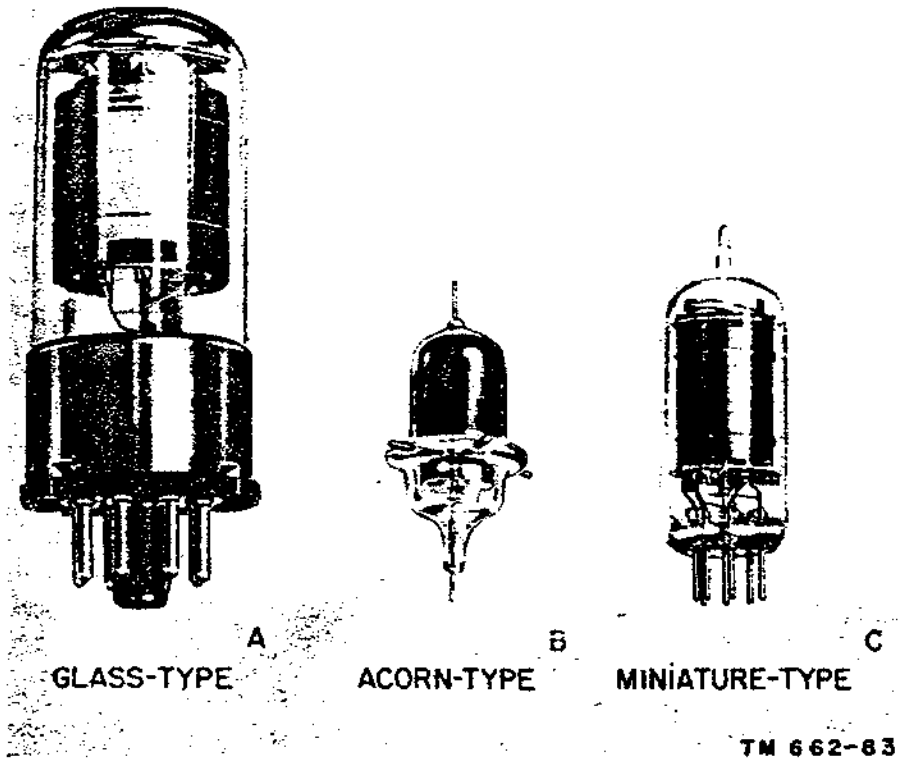


Figure 74. Different types of receiving pentodes.

connection at the top and the control-grid connection at the bottom of the envelope. These are stiff wires which protrude through the envelope. Another type of miniature tube is shown in C.

66. Pentode Circuit

a. When arranged as a basic amplifier, the pentode (fig. 75) is similar to the tetrode (fig. 70). One difference between the two circuits reflects the fundamental difference in behavior between the pentode and the tetrode. In some types of pentodes, the suppressor is electrically connected to the cathode inside the tube; in other types, the connection is made to its own prong on the tube base. Such flexibility of connection between the suppressor and the cathode enables some pentodes to be arranged for action as triodes.

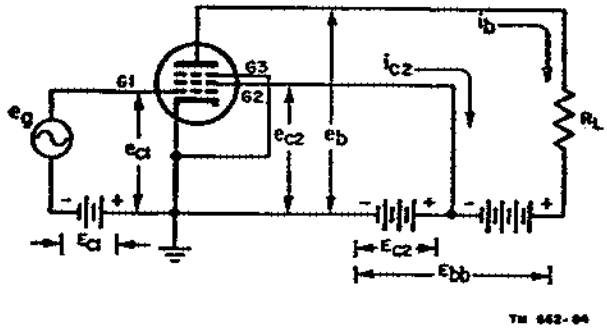


Figure 75. Circuit representation of pentode.

b. The electrode voltage and current notations for a pentode parallel those for the tetrode. The electrical connection between the suppressor and the cathode places the former at the same potential relative to the adjacent electrodes as the cathode. Under the circumstances, the suppressor bears no current or voltage notations of its own. It is viewed as being at 0 or ground potential.

c. Referring again to figure 75, primary electrons are accelerated toward the plate by suitable voltages applied to G1 and G2. They pass through the openings of the control grid and screen wires and also through the openings of the suppressor, G3. When the electrons

strike the plate they do so with sufficient velocity to cause secondary emission.

d. Since the plate is positive with relation to the cathode and the cathode is connected to the suppressor, the suppressor is negative with relation to the plate. Therefore, secondary electrons emitted by the plate are repelled by the suppressor and returned to the plate. Reverse current between plate and screen is therefore avoided, even if the screen voltage momentarily exceeds the plate voltage. The existence of the suppressor between the screen and plate has another beneficial effect. It reduces the control-grid-to-plate capacitance even more than in the tetrode; therefore, it greatly reduces the feedback problem. This is one reason that accounts for the wide application of the pentode.

67. Characteristic Curves

a. The plate family of characteristic curves for a typical pentode (6SJ7) is shown in figure 76. Plate-supply voltage E_{bb} is variable from 0 volts to 400 volts (X-axis). Since the curves are made without a load in the plate circuit, the plate potential $e_b = E_{bb}$. The screen voltage $E_{c2} = e_{c2}$ is held constant at 100 volts; the suppressor is at 0 potential and the control-grid voltage E_{c1} is varied between 0 volts and —5 volts in steps of 1 volt. The filament voltage, E_f, is equal to 6.3 volts.

b. A number of significant details are shown in figure 76. Dips in the curves (fig. 72) due to negative resistance are absent. At no time does the plate current fall with increasing plate voltage. A zone of critical plate potential (the range of plate-voltage changes over which the plate current rises rapidly) still prevails. However, this happens over a limited area only. The top of the knee of the plate-current curve is reached much sooner than in the tetrode.

c. As in the tetrode, the plate current is relatively independent of the plate voltage. The usable portion of each characteristic is to the right of the knee in each curve, where the curves are relatively flat. A significant condition is implied by the unequal spacings of the plate-current curves at the flat portions. Each plate-current curve corresponds to a specific value of control-grid voltage, each of which represents an equal increment of change. The plate current does not change equally for equal changes in control-grid voltage, with the screen and plate voltage fixed in value.

d. The tabulation below shows this plate-current control-grid voltage behavior. The plate voltage is held constant at 300 volts; the screen-

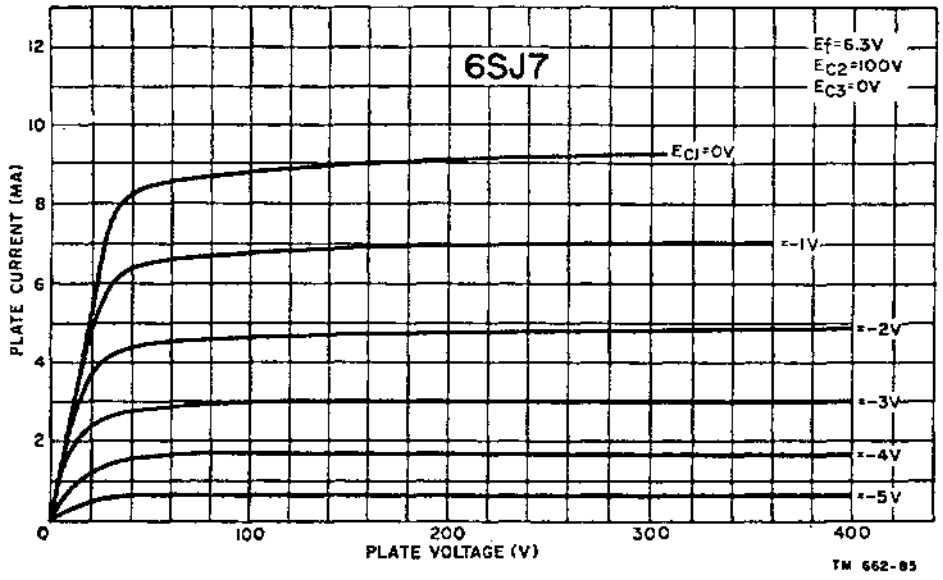


Figure 76. Plate family of characteristic curves for pentode.

grid voltage is constant at 100 volts and the suppressor is joined to the cathode and equals 0 volts.

Plate voltage (E_{bb})	Control grid voltage (E_{c1})	Plate current (i_b)	Plate current change
300	0	9.3 ma	
300	—1	7.0 ma	(9.3 —7.0) = 2.3 ma
300	—2	4.8 ma	(7.0 —4.8) = 2.2 ma
300	—3	3.0 ma	(4.8 —3.0) = 1.8 ma
300	—4	1.6 ma	(3.0 —1.6) = 1.4 ma
300	—5	.6 ma	(1.6 — .6) = 1.0 ma

e. These figures imply a nonlinear behavior between plate current changes and control grid voltage changes, and consequently, the appearance of distortion. Therefore, it can be said that pentode operation is productive of more distortion than is triode operation. By proper choice of operating constants the distortion is reduced to tolerable proportions. The advantages gained from the use of pentodes in certain sections of communications equipment exceed the disadvantages caused by distortion, and therefore, the tube enjoys wide popularity.

68. Constants of Pentodes

a. AMPLIFICATION FACTOR. The amplification factor of a pentode is great, being approximately 1,500 for receiving tube types. This is about 100 times more than the amplification obtainable with triodes, and two to three times as great as the amplification factor of tetrodes. The reason for the unusual amplifying ability of the pentode can be found by graphically locating μ in the plate family of curves in figure 76.

b. PLATE RESISTANCE.

(1) The a-c plate resistance of the pentode is very high. For example, the 6SJ7 pentode has a plate resistance of about 1 megohm, or nearly 200 times greater than the plate resistance of a triode and several times that of a tetrode. The high plate resistance of the tetrode and the pentode sets them apart from the triode in the manner of use with different devices. It is significant to note that the higher the negative grid bias, the higher the plate resistance of the pentode, as can be seen in the characteristic curves.

(2) Some types of pentodes, known as *power pentodes*, manage to keep the plate resistance lower than it is in the usual type of pentode, but even in these varieties r_p is many times the value found in triodes intended for similar uses in communications equipment. The transconductance ratings, however, do not differ greatly from those of triodes designed for similar applications.

c. TRANSCONDUCTANCE.

(1) Despite the high amplification factor of pentodes, the transconductance ratings are comparable to the ratings of triodes and tetrodes because of the extremely high plate resistance found in the pentode. It is obvious, therefore, that the specific change in plate current per unit change in control-grid is very low.

(2) Figure 77 illustrates the variation in transconductance of a typical pentode with changes in control-grid voltage, screen voltage, and plate voltage. The highest values of transconductance prevail for low values of control-grid bias, E_{c1}, high values of screen voltage, E_{c2}, and plate voltage, E_{bb}. With fixed plate voltage, the greater the screen voltage the greater the transconductance. This is understandable because of the great effect that is displayed on the plate current by the screen voltage. Also, in figure 77, a lower value of plate voltage (dotted lines at $E_{bb} = 100$) introduces a lower value of g_m than a higher value of plate voltage ($E_{bb} = 200$), since raising the plate voltage lowers the value of r_p, which in turn raises the value of g_m.

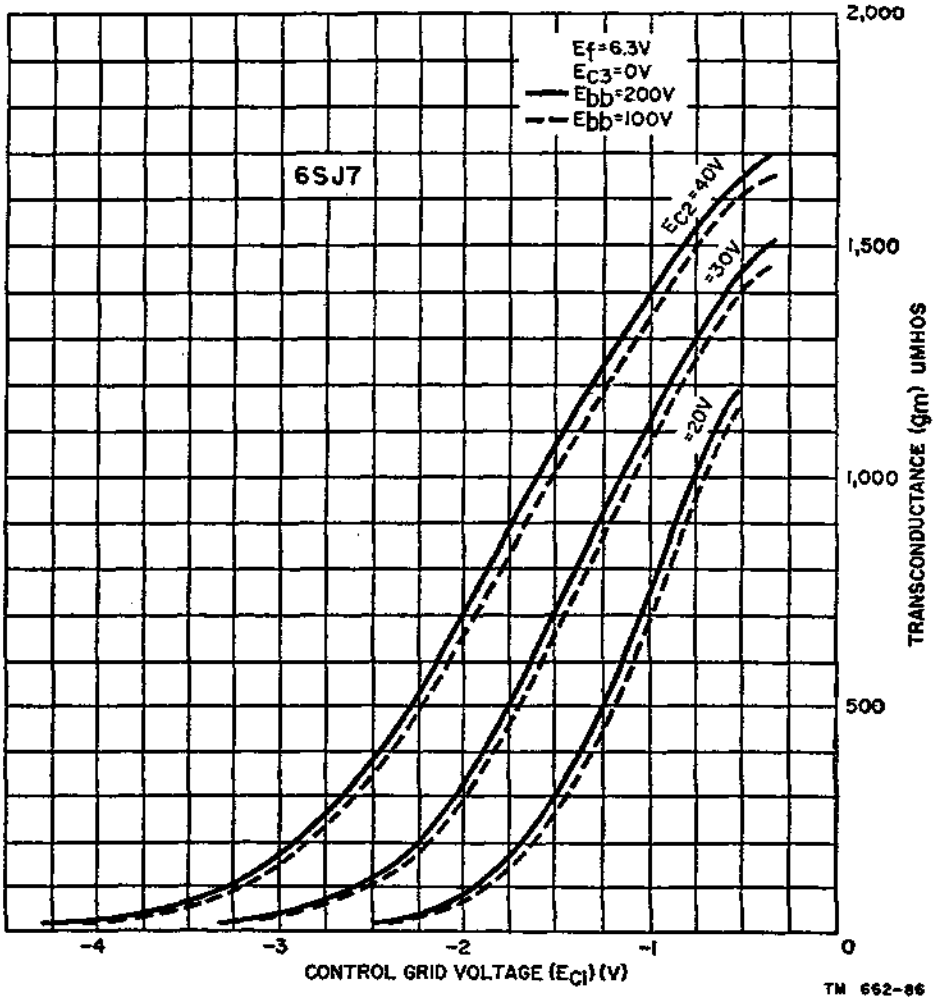


Figure 77. Family of curves showing variation of transconductance of 6SJ7 pentode.

69. Dynamic Transfer Characteristic

a. The development of the dynamic transfer characteristic of a pentode follows the method described for the triode. The effects developed in the pentode as compared with those of the triode are shown in the dynamic transfer characteristics in figure 78. These curves are drawn for a 6SJ7 pentode with $E_{bb} = 300$ volts, $E_{c2} = 100$ volts, and $E_{c3} = 0$ volts. The load lines are for $R_L = 0$ ohms, 30,000 ohms, 50,000 ohms, and 100,000 ohms.

b. The discussion concerning the dynamic transfer characteristics of the triode (pars. 54 and 55) brought out the advantages of linear curves and the desirability of operating over the linear portions of the transfer characteristic curve. This was the condition established for distortionless amplification. It was pointed out, moreover, that the higher the ohmic value of the load, R_L, the straighter was the characteristic, and the more faithful the pattern of changes in plate current relative to the pattern of changes in control-grid voltage.

c. The contrasting conditions encountered in the pentode operated as stipulated are shown in figure 78. The characteristic curves are not straight when R_L equals a finite value. The curve labeled $R_L = 30{,}000$ ohms appears to be the nearest approach to a usable condition, but even this curve is not linear throughout its entire length. As the value of the load R_L is in-

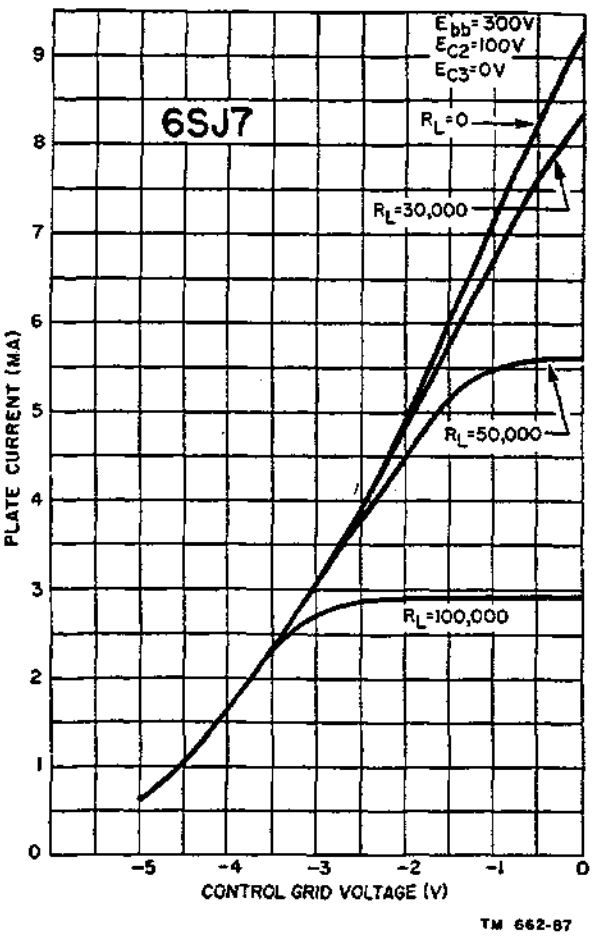


Figure 78. Dynamic transfer characteristic curves of 6SJ7 pentode.

creased, the nonlinearity becomes more pronounced. In fact, the characteristic actually flattens over a range of control-grid voltage changes. Note how flat curve R_L = 100,000 becomes. These flat portions represent very little change in plate current. Dynamic transfer characteristics of this kind are usable under special circumstances, but not when distortionless amplification is desired.

d. The reason underlying the flattening of the dynamic transfer characteristics (fig. 78) is brought out in figure 79. This is the static plate family of the 6SJ7 with load lines drawn on them. Load lines may be drawn very simply on the plate-current plate-voltage characteristics by connecting two points; one point is on the Y-axis (plate current) and the other on the X-axis (plate voltage). On the Y-axis, the point is obtained in the following manner. By Ohm's law, $i_b = E_{bb}/R_L$, or the current through the load resistor, i_b, equals the voltage across it, E_{bb}, over the value of its resistance, R_L. Consequently, for different values of R_L different load lines are obtained. On the X-axis, the point is obtained by applying the value of E_{bb} that is used in the circuity. Under this condition, no plate current is flowing through the circuit and, therefore, no voltage drop appears across the load resistor. The load lines in figure 79 intersect the plate current curves below the knee of each curve, resulting in very little change in plate current as the grid bias is reduced.

e. By reducing the screen voltage, E_{c2}, to perhaps one-seventh or one-tenth of the plate-supply voltage, the slope of the plate-current rise for low values of plate voltage is made very steep. For instance, with a screen voltage of 100 volts (E_{c2} = 100) and a control voltage of 0 volts, the knee of the plate-current curve is reached with the plate-supply voltage equal to approximately 40 volts (fig. 79). When the screen voltage is reduced to 40 volts, the same point is reached with a plate voltage of only about 16 volts. A similar improvement is attained for each value of control-grid voltage. Of course, the reduced screen voltage reduces the plate current, but this is secondary in importance to the improvement in the characteristics and utility.

f. The benefits derived by reducing the value of E_{c2} are shown in the dynamic transfer characteristics illustrated in figure 80. Compare these curves with those in figure 78, especially the curve for R_L = 100,000 ohms. Note that while all curves are nonlinear, the 100,000-ohm load curve approaches R_L = 0 and is without the flat portion shown in figure 78. As a matter of fact, a load somewhat in excess of 100,000 ohms is tolerable. The R_L = 100,000-ohms curve has been straightened because its load

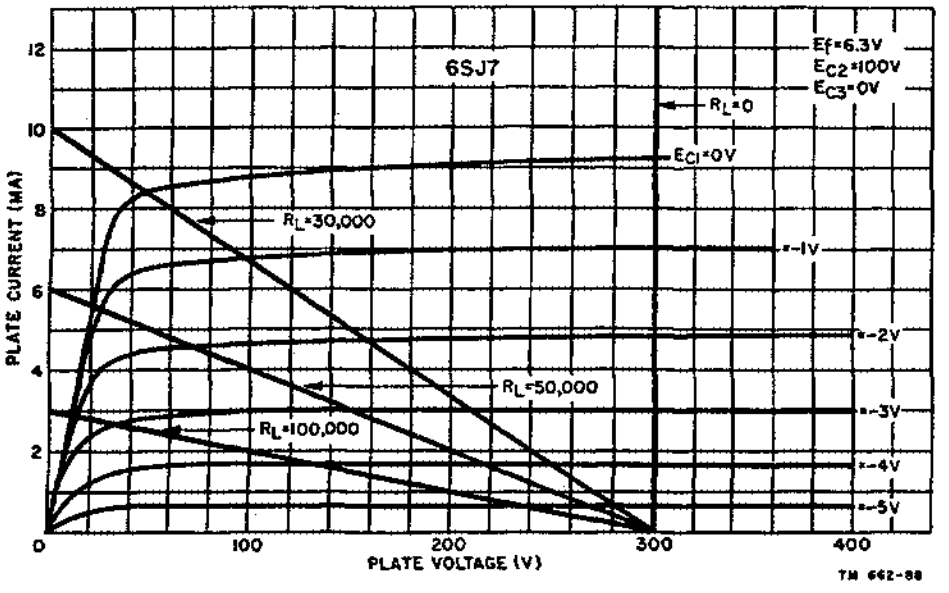


Figure 79. Load lines of 0 ohms, 30,000, 50,000, and 100,000 ohms drawn on plate family of 6SJ7 pentode.

line intersects the static plate-current curves over their relatively flat portions. Curves for R_L = 30,000 and 50,000 are not included in figure 80 because they closely resemble the R_L = 10,000 curve.

g. From the transfer characteristics for R_L = 250,000 ohms and R_L = 500,000 ohms (fig. 80), it is evident that loads in excess of perhaps 150,000 ohms again cause considerable distortion. Even R_L = 200,000 ohms begins to show some reverse curvature.

h. Another significant fact present in figure 80 relates to the usable range of control-grid voltages. Obviously, the control-grid voltage cannot exceed a maximum of slightly more than 2.5 volts, or plate-current cut-off is reached. This sets the operating point at about —1.5 volts. Even then, the curvature in R_L = 0 ohms and R_L = 100,000 ohms indicates unavoidable distortion.

i. Relatively low grid-voltage swing or signal input is a requirement in pentodes. This is a standard compromise. For example, in figure 80, distortion is minimized by selecting —1.25 volts as the operating point and limiting the control-grid voltage swing to about .5 volt peak-to-peak. In this way, the increased curvature of R_L = 100,000 ohms below —1.5 volts does little harm.

70. Beam Power Tube

a. The beam power tube has the advantages of both the tetrode and the pentode tube. This tube is capable of handling relatively high levels of electrical power for application in the output stages of receivers and amplifiers, and in different parts of transmitters. The power-handling capacity stems from the concentration of the plate-current electrons into beams or sheets of moving charges. In the usual type of electron tube the plate-current electrons advance in a predetermined direction but without being confined into beams (fig. 81).

b. The external appearance of these tubes is like that of other receiving-type tetrodes or

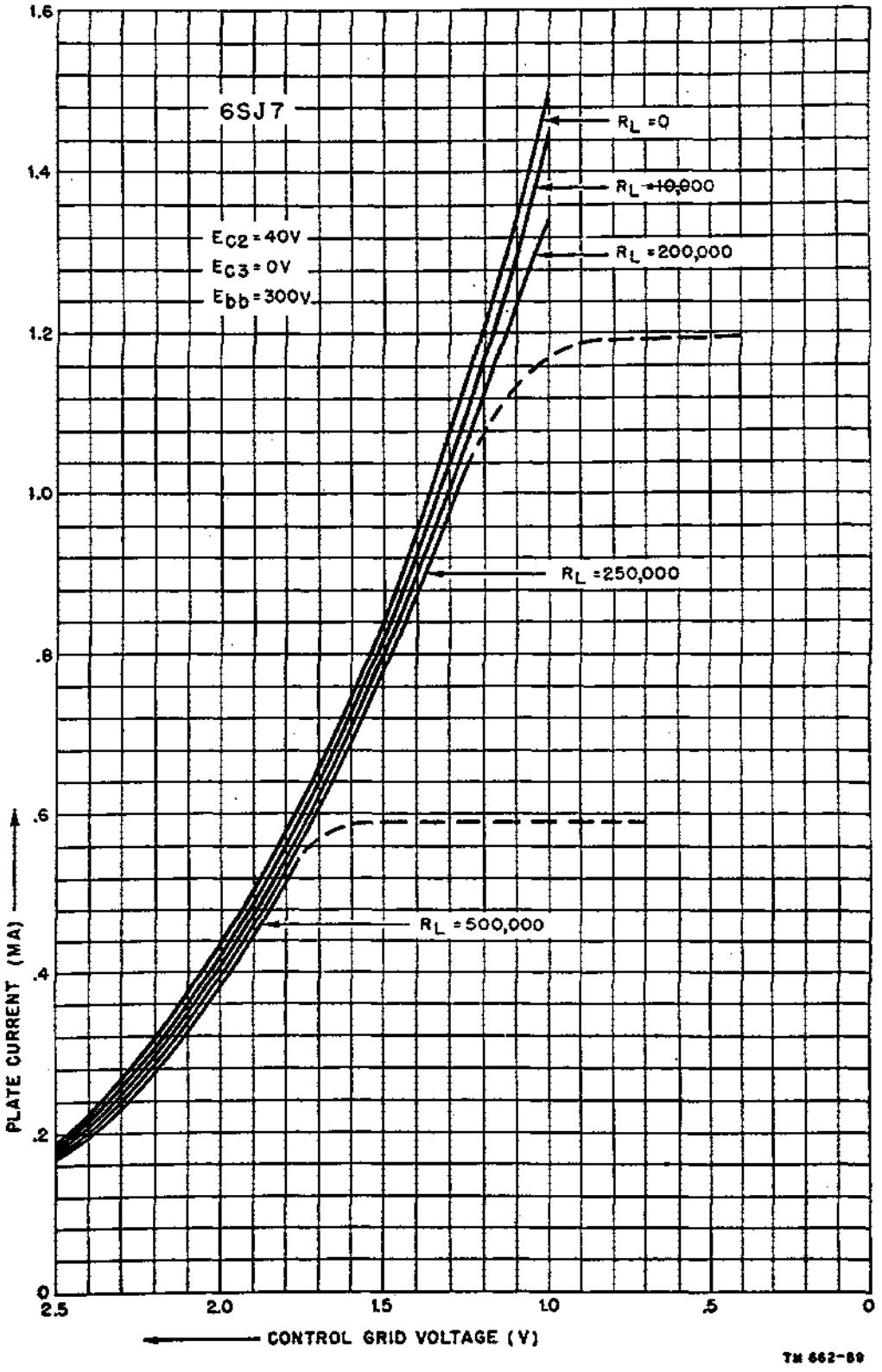


Figure 80. Dynamic transfer characteristic curves of 6SJ7 pentode under improved conditions.

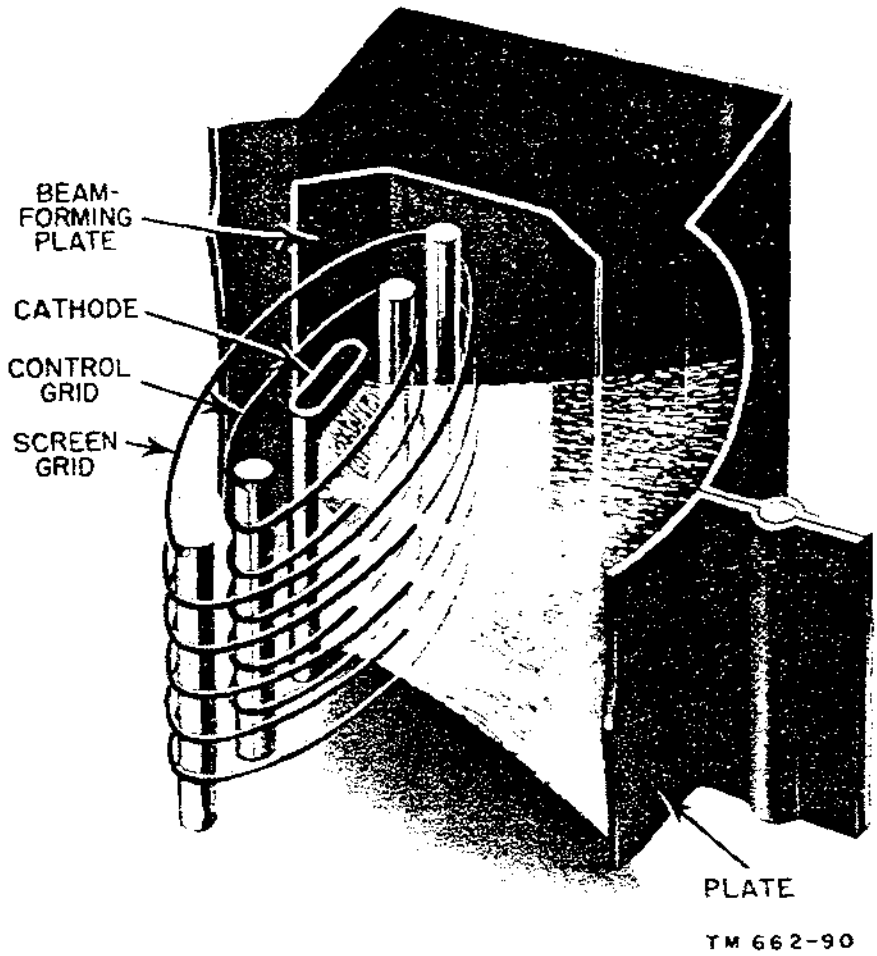


Figure 81. Electrons concentrated into beams in beam power tube.

pentodes. They are slightly larger in dimension because they are called upon to handle somewhat more power, but they have no distinctive external identifying features.

c. The constructional details of a beam power tube which contains beam-forming plates are shown in figure 81. It is not evident, however, that the control-grid and screen-grid electrode windings are of the same pitch, and that the wires of these electrodes are physically in line with each other relative to the paths of the plate-current electrons (fig. 82).

d. A of figure 82 illustrates how the screen-grid wires and control-grid wires in the ordinary tetrode determine the electron paths. The wires are out of alinement; therefore, electrons which pass through the control-grid wires are partly deflected from their paths and many strike the screen wires. This produces a screen current and thus limits the value of plate current.

e. In B the results are different. Because of the arrangement of the control and screen grids, the screen intercepts fewer electrons; therefore, the relative screen current is less in the beam power tube than in the ordinary tetrode, or pentode. In turn, more electrons reach the plate, thereby making the plate current higher.

f. The cumulative effect of the arrangement in B is a tube in which the plate and the control grid are electrically isolated; the plate current is high, the plate resistance is relatively low, and a substantial amount of electrical

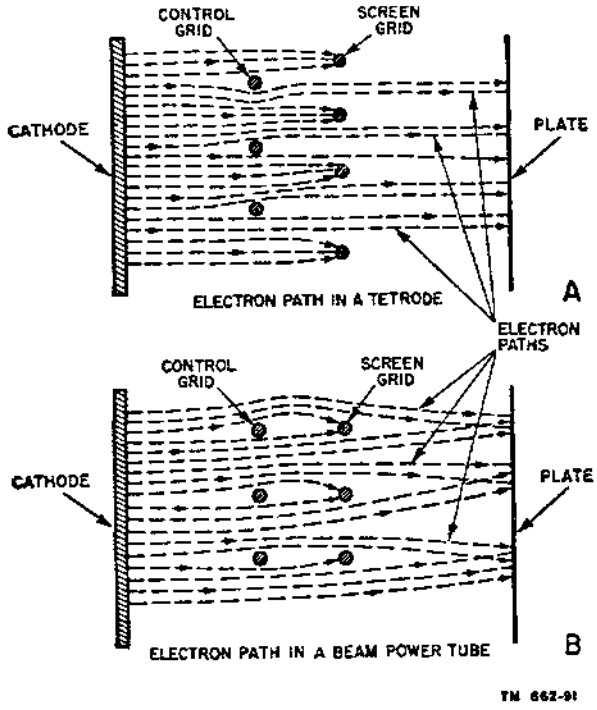


Figure 82. Electron paths in tetrode and beam-power tube.

power can be handled with reduced distortion.

g. The beam-forming plates (fig. 81) further influence the movement of the plate-current electrons from the time they pass the screen electrode and strike the plate. The beam electrodes are connected internally to the cathode and consequently they are at the same potential as the latter.

h. Because of this potential of the beam-forming plates, an effect equivalent to a space charge is developed in the space between the screen and the plate. The effect is as if a surface (dashed lines joining the ends of the beam-forming plates in fig. 83) existed in the screen-plate space. This is identified as the *virtual cathode.* The presence of this electric plane repels secondary electrons liberated by the plate and prevents them from moving to the screen. Figure 83 represents a beam power tube as seen from the top of the envelope.

i. In some tubes, the effect of a virtual cathode is achieved by the use of a third grid in place of the beam-forming plates. The results are identical in both versions. In order to satisfy the two types of construction, two references are made to the symbol of the pentode (fig. 84). A symbolizes the beam power tube with the beam-forming plates and B symbolizes the version in which a grid replaces the beam-forming plate. There is no difference between the symbol shown in B and that of the ordinary pentode (B of fig. 73).

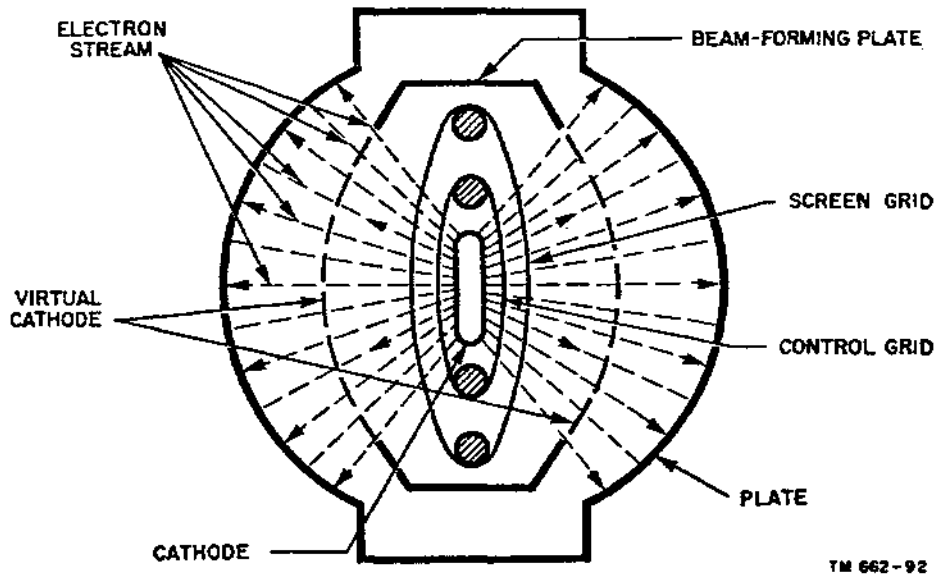


Figure 83. Effect of beam-forming plates on electron flow through beam power tube.

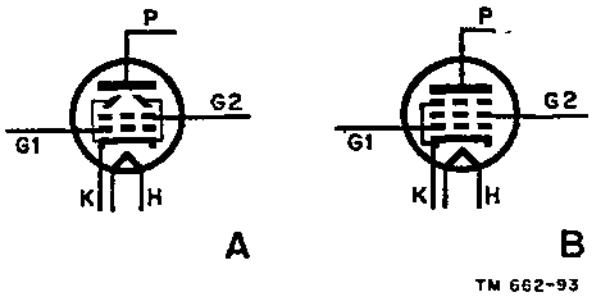
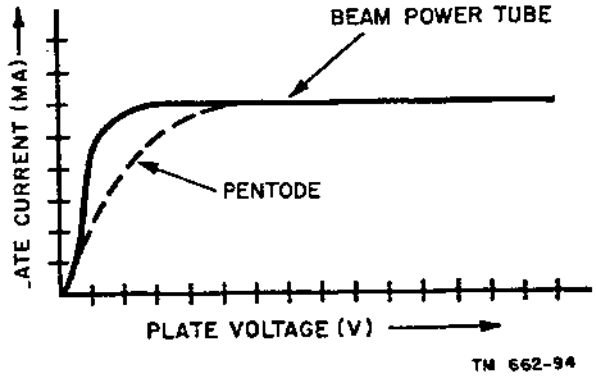


Figure 84. Symbols for beam power tubes.

j. For comparison, figure 85 shows the plate-current plate-voltage characteristics of a beam power tube and of a conventional pentode. Note the rapid rise in plate current for the beam power tube as shown by the solid line. The more gradual rise for the normal pentode shown by the dashed line is an important detail relative to power-handling ability with minimum distortion. The solid-line curve shows that the zone in which the plate current is primarily a function of the plate voltage is much more limited; the plate current becomes substantially independent of plate voltage at much lower values of plate potential. This characteristic enables the beam power tube to handle greater amounts of electrical power at lower values of plate voltage than in the ordinary pentode. In addition, the beam power tube produces less distortion than the ordinary pentode while accommodating an increased grid swing and plate-current change.



Characteristic curve for beam power tube red with same curve for pentode.

71. Pentodes as Triodes

a. Several pentode types are so designed that they can be used as triodes, as labeled in tube data handbooks where information concerning their operating characteristics also is given. Speaking in generalities, the identity of the pentode is lost when the tube is triode-connected. When so arranged, it displays the characteristics of triodes, as outlined in chapter 4.

b. Triode behavior may be accomplished in several ways, as indicated by the principal circuit arrangements in A and B of figure 86. All tube electrodes terminate in pins on the tube base. In A, grids G2 and G3 are connected to the plate. In B, the cathode is connected to the suppressor and the screen grid is connected to the plate.

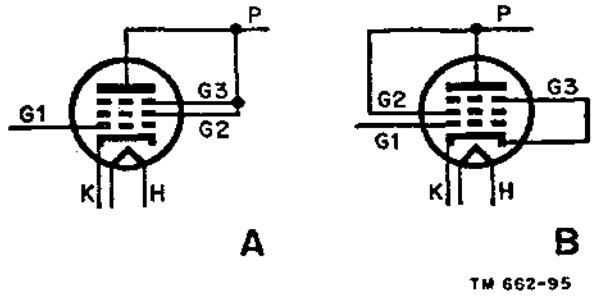


Figure 86. Typical example showing pentode connection to triode.

72. Variable-μ Tubes

a. The amplification constant, or μ, of an electron tube has been described as being a function of the geometry of the tube—that is, of the shape and organization of the electrodes. Slight variations in its value may occur under different operating-voltage conditions but, for all practical purposes, it is considered to remain substantially constant. This accounts for the fact that each vacuum tube bears a single-μ rating which is assumed to be fixed.

b. The amplification constant of a tube expresses the relationship between plate-current cut-off and negative grid voltage when a fixed value of plate voltage is applied. That is, when the input signal, e_g, is made sufficiently negative, the plate current, i_b, is 0 and the plate voltage, E_{bb}, equals e_b. This was explained in chapter 4. High-μ tubes such as tetrodes and

pentodes, especially the latter type, reach plate-current cut-off at relatively low values of negative grid voltage. Low-μ tubes allow the application of much higher negative grid voltages before cut-off is reached.

c. Such plate-current grid-voltage relationships and the fixed-μ constant stem from the kind of control-grid structure used in most of the electron tubes that have been discussed previously. That is, the turns of the control grid are uniformly spaced throughout the length of the structure. The application of a voltage to the control grid results in the same effect on the plate-current electrons all along the control-grid wires.

d. The fixed-μ state poses a problem when high-μ tubes such as tetrodes and pentodes are used in communications systems. Frequently large-amplitude signals are encountered and they must be controlled in the equipment in order to produce the desired intelligence with a minimum of distortion.

e. To minimize these effects, special kinds of tetrodes and pentodes are used. These are known as variable-μ tubes and differ from ordinary tubes in the construction of the control grids. In these tubes the grid wires are unequally spaced. The turns are closer together at the top and bottom of the winding and wider apart at the center. This form of control-grid construction, shown in the metal-type 6SK7 pentode (A of fig. 87), produces a tube which does not have a constant μ; instead, μ changes with the value of grid voltage applied to the control grid.

f. At low values of bias the grid operates in a normal manner. As the control grid is made more negative, the effect of the closely spaced grid wires becomes greater and the electron flow from the space charge in this region is cut off completely. The center of the grid structure also displays a greater effect but still allows electrons to advance to the screen and plate. The over-all reduction in plate current therefore is gradual. Eventually, with sufficient

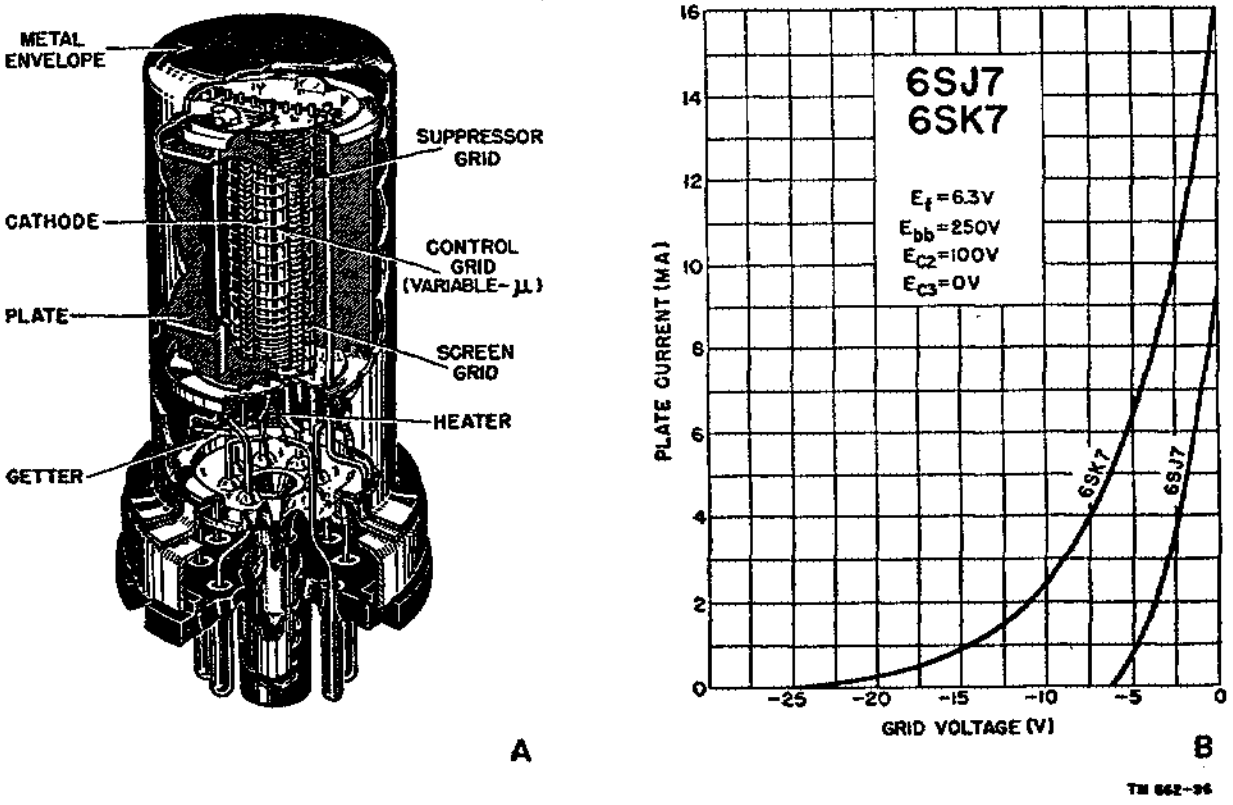


Figure 87. Construction of variable-μ pentode and its plate-current grid-voltage characteristic.

negative voltage on the grid, all parts of the grid electrode winding act to cut off the plate current, but the negative grid voltage required to attain this is perhaps three to four times as much as, if not more than for the conventional tube operated at like screen and plate voltages. The plate-current grid-voltage characteristic of a variable-μ tube, 6SK7, is shown in B of figure 87. A standard pentode curve, 6SJ7, is shown for comparison.

g. Variable-μ tetrodes and pentodes are used in locations in communications equipment where high bias voltages may be necessary to provide control of the signal level.

Section III. MULTIGRID AND MULTIUNIT TUBES

73. Multigrid Tubes

a. INTRODUCTION AND SYMBOLS. Tubes which have more than three grids commonly are referred to as *multigrid* tubes. For instance, if a grid is added to a pentode, a six-electrode multigrid tube results. This tube is known as a *hexode.* The schematic symbol for an indirectly heated hexode is shown in A of figure 88. Other multigrid tubes are the *heptode,* shown in B, which contains five grids, and the *octode,* in C, which has six grids. In these tubes, as in the basic types, the grids are designated in numerical order starting with the control grid, as shown.

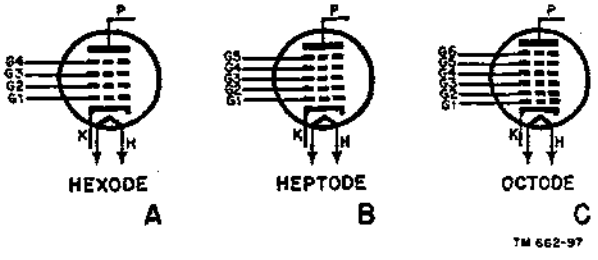


Figure 88. Schematic symbols of multigrid tubes.

b. USES OF MULTIGRID TUBES. The hexode is an experimental tube and is never manufactured commercially. Heptodes, also known as *pentagrid* tubes because of their five grids, are used mostly in frequency converter or mixer circuits. When a heptode is used as a frequency converter, two voltages having different frequencies are each impressed on a separate grid of the tube. Heptodes also are used as volume compressors and expanders. In these applications the gain of an amplifier is controlled automatically. The octode, just as the heptode, also is used as a frequency converter.

c. SUPERHETERODYNE ACTION.

(1) Multigrid frequency-converter tubes are used in superheterodyne receivers. In this application, two different frequencies beat or heterodyne with each other to form additional frequencies called beat frequencies. One of these beat frequencies is equal numerically to the sum of the two applied frequencies; the other beat frequency is equal numerically to their difference. It is possible to obtain the sum and difference frequencies because the tube has a nonlinear dynamic characteristic. In superheterodyne receivers only one frequency output from the converter system is desired. Whether the sum or the difference frequency is chosen, it is known as the intermediate frequency of the receiver. It is common practice to use the difference frequency (fig. 89). The r-f (radio-frequency) input signal from the transmitter and the local oscillator signal are injected simultaneously into the frequency converter. Suppose that the desired intermediate frequency is 465 kc (kilocycles) and that the transmitting station frequency is 1,000 kc. The oscillator then can operate at a frequency of 1,465 kc (1,000 plus 465) to produce the desired intermediate frequency.

(2) Two systems can be used to obtain the desired intermediate frequency. In one system the oscillator is a separate

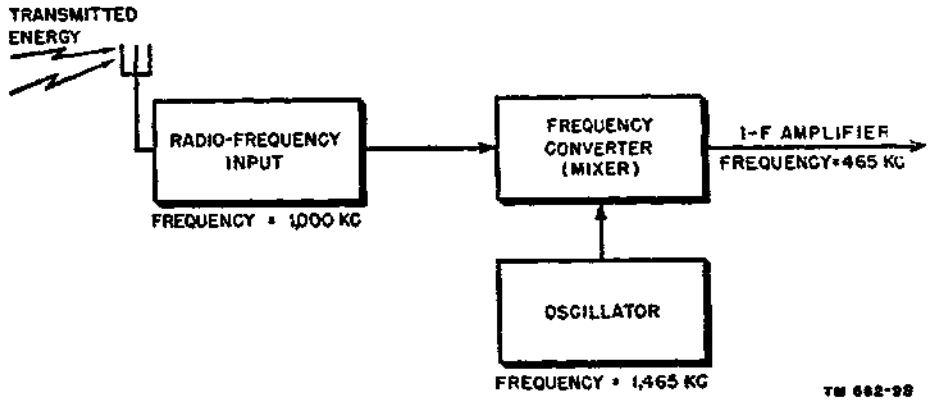


Figure 89. Superheterodyne action.

tube, usually a triode, whose output signal is coupled to the frequency converter tube, usually a pentode or a heptode. In this system the frequency-converter tube commonly is known as a *mixer*. The other system uses a single tube as both the frequency converter and the oscillator. In the latter arrangement, a heptode is used most often. The tube then is known as a *pentagrid converter*. Both systems commonly are found in superheterodyne receivers.

d. PENTAGRID CONVERTER.

(1) The circuit arrangement of a heptode used as a pentagrid converter is shown in figure 90. The purpose of the pentagrid converter is threefold. It acts as an oscillator, as a mixer, to obtain the intermediate frequency, and as an amplifier. The r-f input signal originating at a transmitter is designated as e_g and the oscillator circuit is shown as a block. An L-C (inductance capacitance) tuned circuit is the load. Capacitor C is made variable to tune the circuit to the intermediate frequency. The d-c operating potentials are indicated by E_{cc}, E_{bb}, and E_{c2}.

(2) The pentagrid converter tube can be considered as made up of two parts, a triode and a tetrode. In the triode section, K is the cathode, G1 is the control grid, and G2 operates as the plate. Physically, G2 consists only of a pair of vertical rods across which no grid wires are strung. For the tetrode section, G4 is the control grid, G3 and G5 are the screen grids, and P is the plate. Grids G3 and G5 are connected

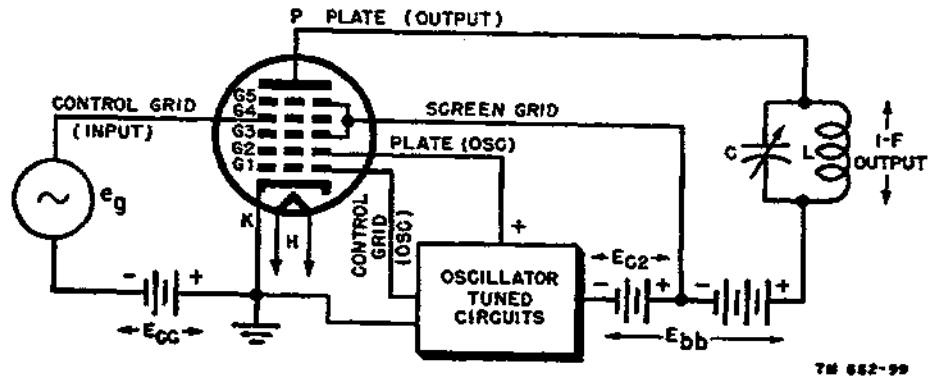


Figure 90. Pentagrid converter circuit.

internally as shown. G3 prevents interaction between the oscillator circuits and the r-f input signal circuits. G4 prevents interaction between the i-f (intermediate-frequency) output on the plate and e_g. The cathode for the tetrode section exists virtually between G3 and G4.

(3) Electrons emitted from the surface of the cathode, K, are influenced by the various elements within the tube. In practice, G1 receives 3 to 6 percent of the electrons emitted, G2 receives about 40 percent, G3 and G5 receive about 25 to 30 percent, and the plate receives the remaining electrons, about 30 percent. The tube is biased so that G4 does not draw current.

(4) Oscillation is produced because of feedback from G2 to G1 in the oscillator circuit. This causes G1 to become alternately positive and negative. Consequently, the current flow through the tube is alternately increased and decreased. Many of the electrons which approach G2 flow beyond it, because of its open structure, even though it is highly positive. Electrons passing G2 are further accelerated by the high positive potential of G3. Grid G4 is always negative, and therefore tends to retard the electrons approaching it. This action produces a virtual cathode between G3 and G4. The electron flow from this virtual cathode is varied or modulated by the r-f signal, e_g, that is injected on G4. The electrons then are drawn to the plate, which is highly positive.

(5) If G1 is slightly negative, or even somewhat positive, the virtual cathode is able to supply the plate of the tetrode section with sufficient electrons. On the other hand, if G1 is made very negative, a deficiency of electrons exists at the virtual cathode which may even cut the tube off. As a result of this variation in the virtual cathode, a current is produced at plate P which varies at the oscillator frequency. However, the electron stream is further modulated by the signal injected on G4. In this way, both the oscillator signal and the r-f input signal on G4 modulate the electron stream, with the result that i-f signals are produced in the plate circuit. The L-C tuned circuit selects the desired intermediate frequency.

(6) Several tube types can be used in the circuit shown in figure 90. Examples are the 1A7, 6A7, 6A8, and 7B8. These tubes operate satisfactorily at medium and low frequencies. However, because of reduced oscillator output and undesirable interaction effects at higher frequencies, other pentagrid converters sometimes are used. In this type no electrode operates solely as the oscillator plate (fig. 91).

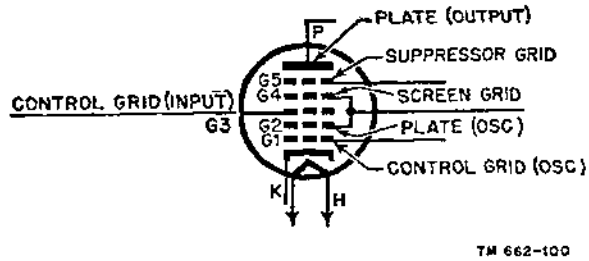


Figure 91. Another form of pentagrid converter.

(7) This form of pentagrid converter can be considered as a triode and a pentode. The triode section forms the oscillator and consists of cathode K, control grid G1, and grid G2. The r-f signal input is injected into G3. Grid G4 is connected internally to G2. The two grids serve as the screen grid of the pentode section in addition to the plate of the triode (oscillator) section. They also minimize any interaction between the oscillator and input signal circuits by shielding G3. Grid G5 is the suppressor of the pentode section; in some tubes it is connected internally to the cathode; in other heptodes it has an external pin connection. Ex-

amples of heptodes with a suppressor grid are the 1R5, 6SA7, 7G7, 12SA7, and 14Q7.

74. Multiunit or Dual-purpose Tubes

a. A multiunit or dual-purpose tube is one in which two or more individual tube-element structures are combined within a single envelope. As a result, compactness, economy, and more satisfactory operation for certain purposes are achieved. The most commonly used multiunit tubes, known as duo-diodes and duo-triodes, combine two diode or two triode elements. Frequently, a single common cathode is used which supplies electrons to both sets of elements in the multiunit tube. Occasionally, an electrode of one set of elements is connected internally to an electrode of another set of elements.

b. There are many types of multiunit tubes, used for a wide variety of purposes. The schematic symbols of the most common ones are shown in figure 92. The tube whose symbol is shown in A can be used as a full-wave rectifier, an f-m (frequency-modulated) discriminator, or a combination detector and avc (automatic volume control) rectifier. The diode-triode, in B, can be used as a diode detector and a triode amplifier. The duo-triode, in E, is used as a push-pull amplifier, two amplifiers in cascade, or as a special type of complex-wave generator. The triode-hexode, in L, and the triode-heptode, in M, are used as mixer-oscillators in superheterodyne receivers.

c. Table I lists typical examples of multipurpose tubes to be found in receiving-type equipment. The letters in the first column refer to the symbols used in figure 92.

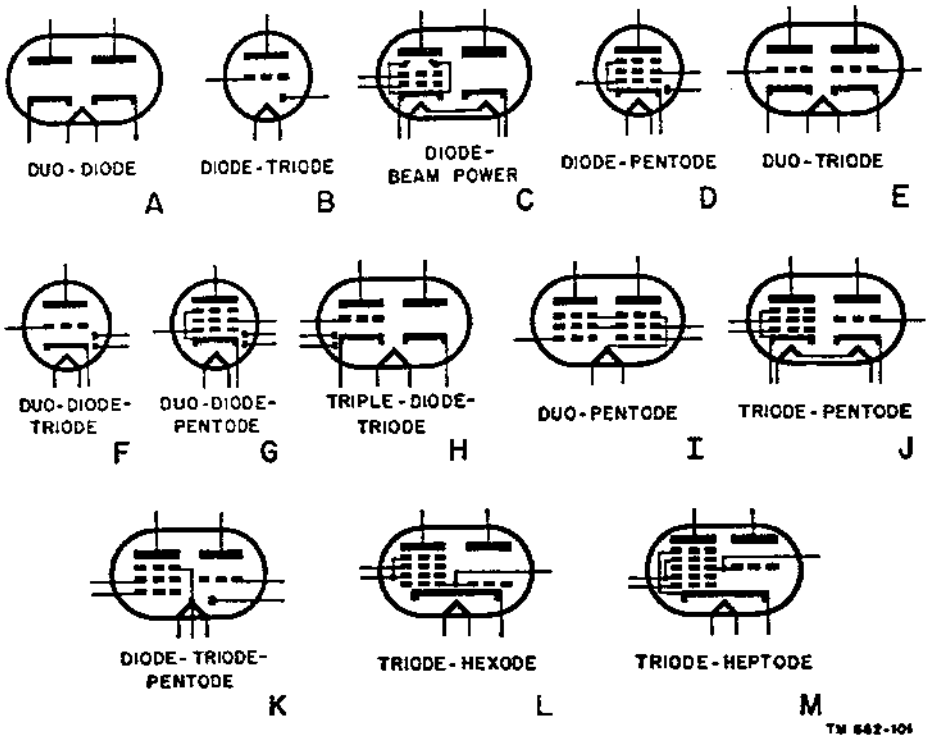


Figure 92. Tube symbols for multiunit tubes.

Table I. Examples of Multipurpose Tubes in Receiving Equipment

Symbol designation	Multipurpose tube	Examples of tube types
A	Duo-diode	5U4, 5V4, 5Y3, 6AL5, 6X5, 12AL5
B	Diode-triode	1H5, 1LH4
C	Diode-beam power	70L7, 117L7, 117N7, 117P7
D	Diode-pentode	1N6, 1T6, 6SF7, 12A7, 12SF7
E	Duo-triode	1J6, 6J6, 6N7, 6NS7, 6SL7, 12AT7, 12AU7
F	Duo-diode-triode	1H5, 6AQ7, 6SQ7, 6V7, 7K7, 7X7, 12SQ7
G	Duo-diode-pentode	1F6, 7R7, 14E7, 14R7
H	Triple-diode-triode	6S8, 6T8, 12S8
I	Duo-pentode	1E7
J	Triode-pentode	6AD7, 6P7, 25B8
K	Diode-triode-pentode	3A8
L	Triode-hexode	6K8, 12K8
M	Triode-heptode	7J7, 7S7, 14J7

Section IV. SUMMARY AND REVIEW QUESTIONS

75. Summary

a. The use of a triode is unsatisfactory in high-frequency systems because of feedback which is caused by interelectrode capacitance.

b. A tetrode contains an electron emitter, a control grid, a screen grid, and a plate.

c. In receiving-type tetrodes, the cap on the top of the tube is connected to the control grid. In transmitting-type tetrodes, the cap is connected to the plate to reduce the capacitance between control grid and plate.

d. In a tetrode, the screen grid is made positive with relation to the cathode. In most cases the d-c screen voltage is appreciably less than the d-c plate voltage.

e. The main purpose of the screen grid is to reduce the interelectrode capacitance between the plate and control grid, thereby preventing self-oscillation.

f. The plate current in a tetrode is not greatly affected by changes in plate voltage.

g. Secondary emission occurs in a vacuum tube when electrons from the space charge strike the plate with sufficient force to dislodge secondary electrons from the plate itself.

h. The movement of secondary electrons in the opposite direction to the regular current flow results in a dip in the plate-current plate-voltage characteristic curve of a tetrode.

i. In a tetrode, r_p and μ are high and g_m remains about the same as in a triode.

j. The main advantage of a tetrode compared to a triode is that it has lower interelectrode capacitance between control grid and plate and it affords greater amplification.

k. The pentode uses a suppressor grid to reduce the effects of secondary emission.

l. The pentode produces more distortion than the triode but it is more widely used because of its other advantages.

m. The beam power tube is capable of handling high power levels. It is used in the output stages of receivers and amplifiers and in various parts of transmitters.

n. To minimize the undesirable effects of distortion, variable-μ tubes are used. In these tubes, the amplification factor is determined by a nonuniform grid structure.

o. A six-electrode tube is a hexode; a seven-electrode tube is a heptode; and an eight-electrode tube is an octode. These are called *multigrid tubes.*

p. A tube which contains five grids and is used to operate as a frequency converter in a superheterodyne receiver is known as a pentagrid converter.

q. Multiunit tubes contain more than one set of elements within a single envelope.

76. Review Questions

a. Why are triodes undesirable for amplification at high frequencies?

b. What are the fundamental differences between the triode, the tetrode, and the pentode?

c. To what electrode is the metal cap on top of a receiving tube usually connected?

d. What is the difference between single-ended and double-ended tubes?

e. What are the major differences between the circuits for a triode and a tetrode?

f. What is the approximate value of inter-electrode capacitance in a triode? In a tetrode?

g. Do changes in E_{bb} affect the total current, $i_b + i_{c2}$, flowing through a tetrode? Why?

h. Explain what is meant by secondary emission.

i. Why do *dips* appear in plate-current plate-voltage characteristic curves of tetrodes?

j. How do the plate-current plate-voltage characteristic curves of modern tetrodes differ from those of the older types?

k. Generally speaking, how do μ, g_m and r_p of a tetrode compare with the same characteristics of a triode?

l. How does a suppressor grid reduce the effects of secondary emission?

m. In external appearance, what is the difference between the tetrode and the pentode?

o. Does the suppressor grid in a pentode reduce the control grid-to-plate capacitance more than the screen grid in a tetrode?

p. How do the plate-current plate-voltage characteristic curves of a pentode compare with those of a tetrode? A triode?

q. Why are pentodes used more often than triodes even though they produce more distortion?

r. Compare r_p, g_m, and μ of a pentode and a triode.

s. Why is the g_m of a pentode about the same as the g_m of a triode and a tetrode?

t. Why are the dynamic transfer characteristic curves of most pentodes not linear?

u. What effect is noted on the dynamic transfer characteristic if the screen voltage is reduced to about one-seventh the value of the plate supply voltage?

v. What are the electrical and physical differences between beam power tubes and ordinary tetrodes and pentodes?

w. How does the physical arrangement of the screen grid in a beam power tube help produce a greater concentration of electrons?

x. What are the physical and electrical differences between a variable-μ pentode and an ordinary pentode?

y. What determines the amplification factor of a tube?

z. What is the difference between a multigrid and a multiunit tube?

CORRECTED COPY **TM 11-662**
C 1

TECHNICAL MANUAL

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

TM 11-662
CHANGES No. 1

DEPARTMENT OF THE ARMY
WASHINGTON 25, D. C., *8 November 1955*

TM 11-662, 20 February 1952, is changed as follows:

Page 36, paragraph 27. Make the following changes in paragraph 27:

a. Line 12. Delete "$-(i_p \times r_p)$" from the equation.

a. Delete lines 14 and 15.

Delete *b.*

Page 43, paragraph 32f(2). Line 4. Change "in reference to ground" to read: in reference to the cathode.

Page 60, paragraph 46a. Make the following changes:

Second column, line 15. Change "It is a pure" to read: The amplification factor is a pure.

Line 30. Change "$\mu = \frac{10}{.1} = 100$" to read:

$$\mu = \frac{10}{.1} = 100.$$

Page 61, figure 55. In the figure caption, change the word "amplifiaction" to read: amplification.

Page 64, paragraph 48c. Change the heading to read: Ac Plate Resistance.

Page 65, paragraph 48. Make the following changes in paragraph 48:

c(3). Line 15. Change "C" to read: 0.

e. Change "R_p" in the heading to read: r_p.

Page 66, paragraph 49d. Change "G_M" in the heading to read: g_m.

Page 67, paragraph 49e. Change "G_M" in the heading to read: g_m.

Page 67, paragraph 50. Change "R_p" in the heading to read: r_p.

Page 72, paragraph 52c(2). Make the following changes:

In line 17 of the second column, on the page, change "E_{b_1}" to read: E_b.

Line 19 of the second column. Change "horizontal" to read: vertical.

Page 73, paragraph 52c(2). Line 5. Change "horizontal" to read: vertical.

Page 74.

f. (Added) *Use of Load Line to Illustrate Amplification.* The output signal voltage and plate current that will result from a given input (grid) signal voltage can be clearly seen by using a load line on a plate family of characteristics. The grid input signal causes the grid voltage to vary along the load line. If an input signal with a swing of 0 to −8 volts is drawn perpendicular to the load line (e_s, fig. 61.1), the output signal voltage may be obtained by drawing vertical lines from the maximum and minimum grid voltage points on the load line to the plate voltage axis. It can be seen that the plate voltage swing, e_p, and consequently, the output signal, is 125 volts. Therefore, an input grid signal of 8 volts is amplified by the tube to an output signal of 125 volts. However, the output wave form (fig. 61.1) may appear smaller than the input. This is because the scale on which the output voltage is drawn (plate volts scale) differs from that on which the input signal is drawn (grid bias scale). The plate current variation, i_p, can be seen by drawing horizontal lines to the plate current axis. This shows that the plate current varies between 5.3 and 10.3 milliamperes. Thus, by plotting the input signal wave form on a load line, the relationship, at any instant, between the input and output signals may be quickly and easily determined.

TAGO 9652A—Nov.

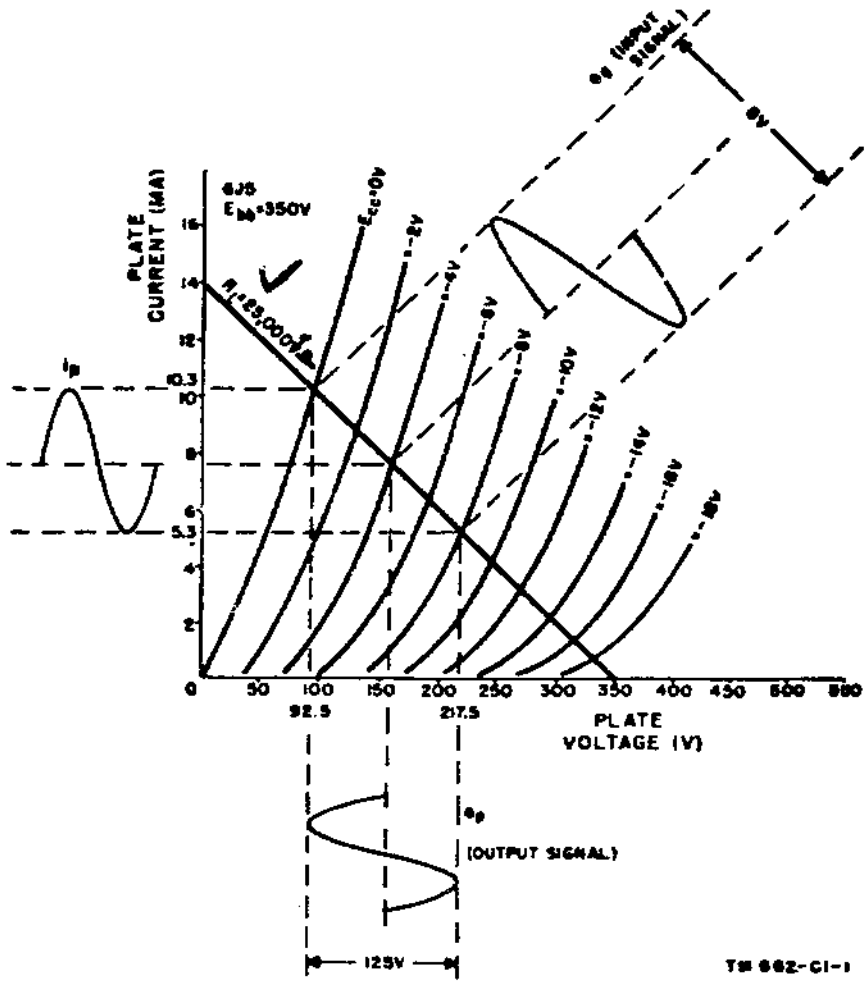


Figure 61.1. (Added) *Plate characteristics showing signal voltage amplification.*

Page 91, paragraph 62h. Line 4. Change ".5" to read: 1.5.

Page 94, paragraph 66. Make the following changes in *a*:

Line 2 of the second column of the page. Delete "as in figure 75."

Line 4. Change "in other types, the connection is" to read: **in other types as in figure 75, the connection is.**

Page 96, paragraph 67a. Line 6. Change "$e_b = e_{bb}$" to read: $e_b = E_{bb}$.

Page 116, figure 96. Place the letter "L" at the intersection of the plate current axis and the characteristic curve.

Page 150, paragraph 90a(1). Line 18. Change "changes negligibly and" to read: **changes negligibly throughout the middle frequency range and.**

TACO 9653A

Page 130, paragraph 90b(1). Line 5. Change "low-middle and high-frequency" to read: **low-, middle-, and high-frequency.**

Page 135, paragraph 92d. Line 9 in the second column on the page. Change "20×20=40" to read: **20×2=40.**

Page 138, paragraph 95a. Line 5. Change "minus" to read: **equals.**

Page 144, paragraph 101b(1). Delete the fourth sentence and substitute the following: **The direction of the electron current flow is opposite to the direction of the arrowhead in the schematic symbol for the crystal.**

Page 145, figure 118. Reverse the connections to the symbol for the crystal. Connect point A to the arrowhead and connect the flat portion of the crystal symbol to the resistor.

Page 145, figure 119. Reverse the connections to the symbol for the crystal. Connect the generator to the arrowhead and connect the flat portion of the crystal symbol to the junction of the capacitor and the resistor.

[AG 413.44 (4 Oct 55)]

BY ORDER OF THE SECRETARY OF THE ARMY:

MAXWELL D. TAYLOR,
General, United States Army,
Chief of Staff

OFFICIAL:

JOHN A. KLEIN,
Major General, United States Army,
The Adjutant General.

DISTRIBUTION:

Active Army:

CNGB (1)
Tec Svc, DA (1) except CSIGO (30)
Tec Svc Bd (1)
Hq CONARC (5)
CONARC Bd (Incl ea Test Sec) (1)
Army AA Comd (2)
OS Maj Comd (5)
OS Base Comd (5)
Log Comd (5)
MDW (1)
Armies (5)
Corps (2)
Tng Div (2)
PMST Sig Sr. ROTC units (1)
Ft & Cp (2)
CGSC (3); ICAF (3); AFSC (5)
Gen & Br Svc Sch (5) except Sig Sch (25); Engr, Armd, Inf & Arty Sch (50)
Gen Depots (2) except Atlanta Gen Depot (None)
Sig Sec, Gen Depots (10)
Sig Depots (20)
POE (2)
OS Sup Agencies (2)
Sig Fld Maint Shops (3)
Sig Lab (5)
Mil Dist (1)
Units organized under following TOE's:
11-7R, Sig Co, Inf Div (2)
11-16R, Hq & Hq Co, Sig Bn, Corps or Abn Corps (2)
11-57R, Armd Sig Co (2)
11-127R, Sig Rep Co (2)
11-128R, Sig Depot Co (2)
11-500R (AA-AE), Sig Svc Org (2)
11-557R, Abn Sig Co (2)
11-587R, Sig Base Maint Co (2)
11-592R, Hq & Hq Co, Sig Base Depot (2)
11-597R, Sig Base Depot Co (2)

NG: State AG (6); units—same as Active Army except allowance is one copy to each unit.
USAR: None.
For explanation of abbreviations used, see SR 320-50-1.

827-164

TECHNICAL MANUAL

BASIC THEORY AND APPLICATION OF ELECTRON TUBES

TM 11-662
CHANGES No. 2

HEADQUARTERS,
DEPARTMENT OF THE ARMY
WASHINGTON 25, D. C., *21 April 1958*

TM 11-662, 20 February 1952, is changed as follows:

Change "R_L=25,000V" on the loadline to: R_L=**25,000Ω** in the following places:

Page 72, figure 61.

Page 74, figure 61.1 (page 2 of C 1).

Page 17, paragraph 16*b*. Make the following changes:

Line 4. Change "attract" to **repel.**

Line 5. Change "repel" to **attract.**

Page 38, paragraph 30*f*. Delete subparagraph *f* and substitute:

f. Static characteristics are obtained with different dc potentials applied to the tube electrodes, whereas dynamic characteristics are obtained with a load in the circuit.

Page 58, paragraph 43*d*(3), last sentence. Change "charge" **to change.**

Page 62, paragraph 47*b*(3), line 4. Change "−9" **to −8.**

Page 64, paragraph 48*c*. Make the following changes:

Line 6. Change "265" **to 285.**

Line 8. Change "33,100" **to 35,625.**

[AG 413.44 (24 Mar 58)]